



US009455647B2

(12) **United States Patent**
Takeuchi et al.

(10) **Patent No.:** **US 9,455,647 B2**
(45) **Date of Patent:** **Sep. 27, 2016**

(54) **ELECTRET ELEMENT AND VIBRATION
POWER GENERATING DEVICE USING THE
SAME**

(71) Applicants: **Panasonic Corporation**, Osaka (JP);
IMEC vzw, Leuven (BE)

(72) Inventors: **Hiroki Takeuchi**, Osaka (JP); **Vladimir
Leonov**, Leuven (BE)

(73) Assignees: **PANASONIC CORPORATION**,
Osaka (JP); **IMEC vzw**, Leuven (BE)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 414 days.

(21) Appl. No.: **14/074,096**

(22) Filed: **Nov. 7, 2013**

(65) **Prior Publication Data**
US 2014/0145554 A1 May 29, 2014

(30) **Foreign Application Priority Data**
Nov. 26, 2012 (JP) 2012-257364

(51) **Int. Cl.**
H02N 1/00 (2006.01)
H02N 2/00 (2006.01)
H01L 41/00 (2013.01)
H02N 1/08 (2006.01)

(52) **U.S. Cl.**
CPC **H02N 1/08** (2013.01)

(58) **Field of Classification Search**
CPC H02N 1/08; H02K 41/03
USPC 310/309, 363, 364, 308
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,267,076 A * 11/1993 Brousseau G02F 1/361
307/400
5,565,717 A * 10/1996 Lewiner H01G 7/02
264/436
5,920,454 A * 7/1999 Nomura H05K 1/162
361/313

2004/0007877 A1 1/2004 Boland et al.

(Continued)

FOREIGN PATENT DOCUMENTS

FR 2968135 A1 * 6/2012 H02N 1/08
JP 2005-529574 9/2005

(Continued)

OTHER PUBLICATIONS

H. Amjadi, "Charge Storage in Double Layers of Thermally Grown
Silicon Dioxide and APCVD Silicon Nitride", IEEE Transactions
on Dielectrics and Electrical Insulation, vol. 6, No. 6, Dec. 1999.

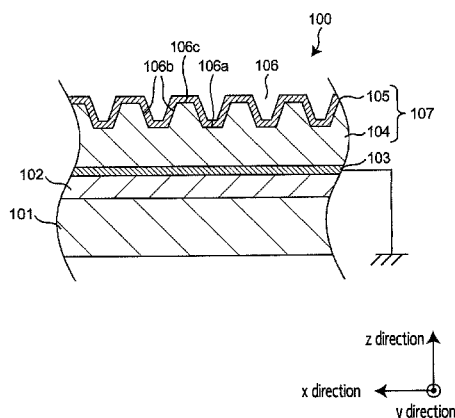
(Continued)

Primary Examiner — Jose Gonzalez Quinones
(74) *Attorney, Agent, or Firm* — Wenderoth, Lind &
Ponack, L.L.P.

(57) **ABSTRACT**

In an electret element **100** including a substrate **101**, an
electrically-conductive electrode **103**, and an electret layer
107 including a first dielectric layer **104** and a second
dielectric layer **105**, when electrical charge charged in the
electret layer **107** is negative, a bottom E_c of conductive
band of the second dielectric layer **105** is lower than a
bottom E_c of the first dielectric layer **104**, and when the
electrical charge is positive, a top E_v of valence band of the
second dielectric layer **105** is higher than a top E_v of the first
dielectric layer **104**; and a concave portion **106** is formed in
a surface of the first dielectric layer **104**; and the second
dielectric layer **105** is formed to cover the entire of the
bottom face **106a** and at least a part of the side wall **106b** of
the concave portion.

21 Claims, 22 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

2004/0016120	A1	1/2004	Boland et al.
2004/0077119	A1*	4/2004	Ikeda B81C 1/00611 438/52
2004/0201946	A1*	10/2004	Iwamatsu H01T 23/00 361/230
2008/0111444	A1	5/2008	Mabuchi
2010/0052469	A1	3/2010	Naruse et al.
2010/0109472	A1	5/2010	Naruse et al.
2011/0163615	A1*	7/2011	Leonov H01G 7/02 307/400
2013/0241346	A1*	9/2013	Boisseau H02N 1/08 310/300

FOREIGN PATENT DOCUMENTS

JP	2008-141171	6/2008
WO	2008/053794	5/2008

OTHER PUBLICATIONS

Yoshihiko Sakane et al., "The development of a high-performance perfluorinated polymer electret and its application to micro power generation", Journal of Micromechanics and Microengineering 18 (2008) 104011.

* cited by examiner

Fig. 1

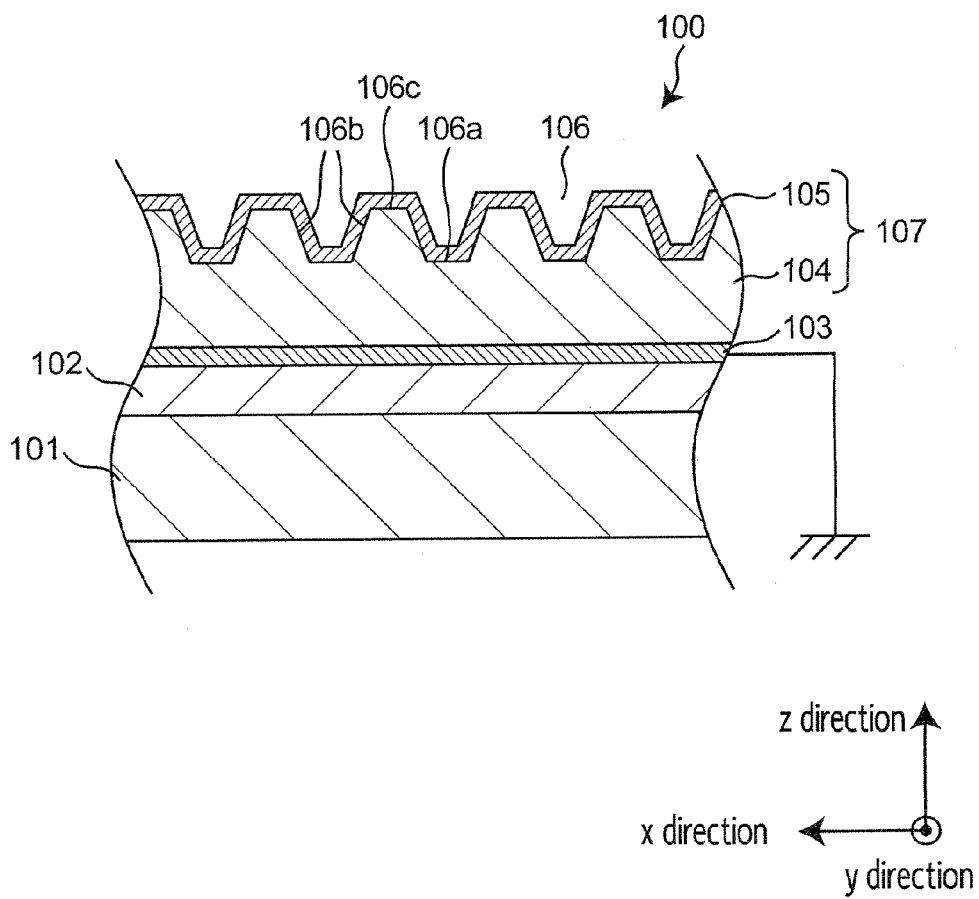


Fig. 2

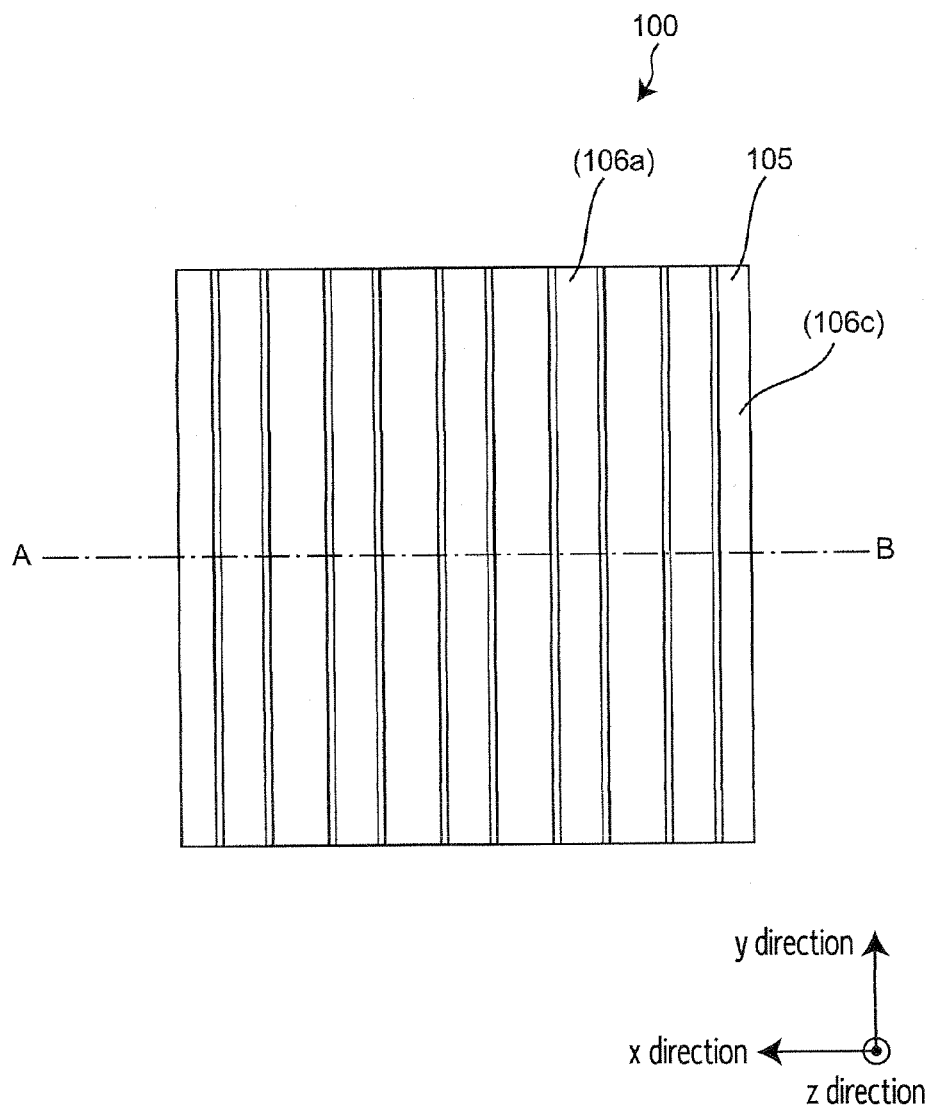


Fig. 3

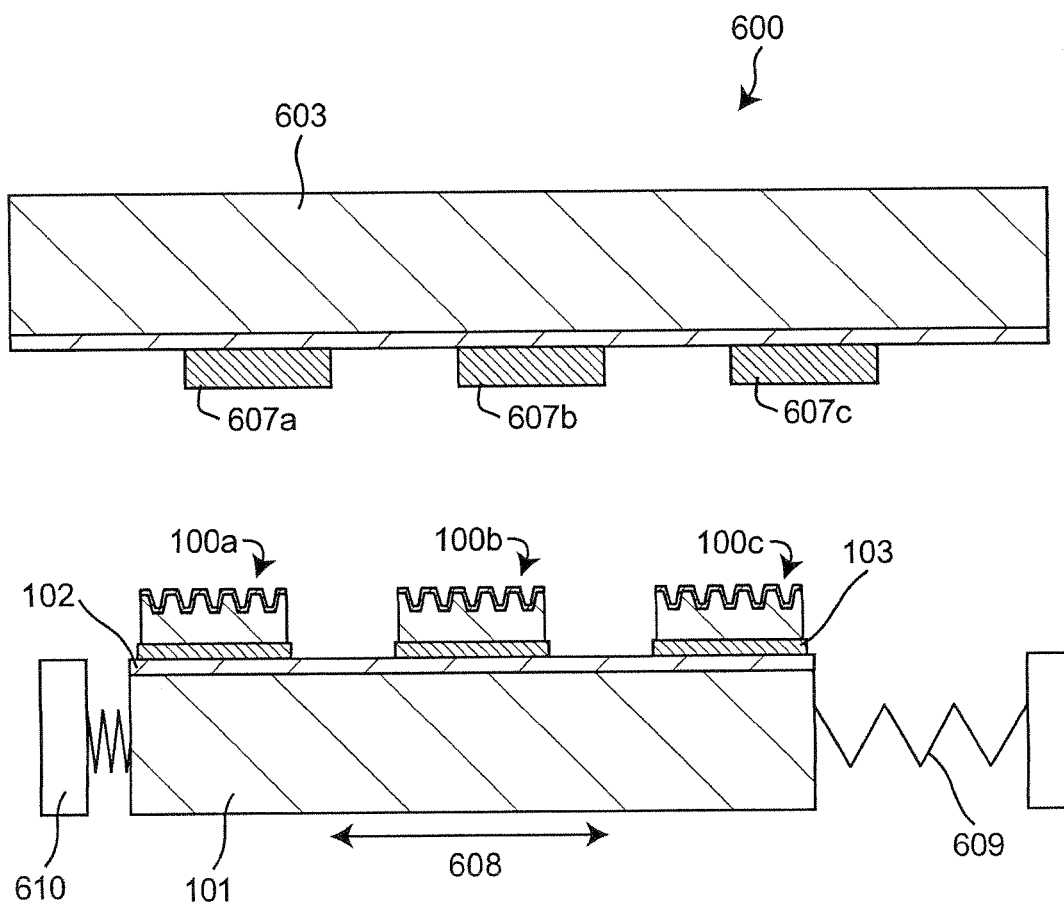


Fig. 4

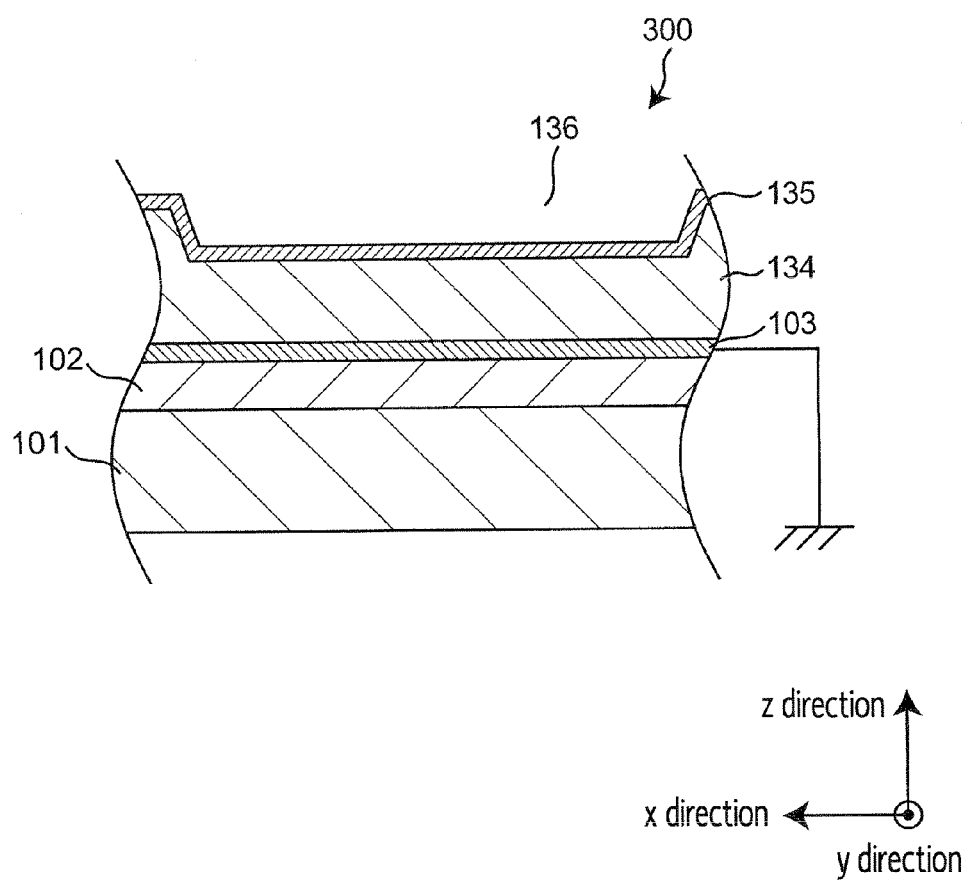


Fig. 5

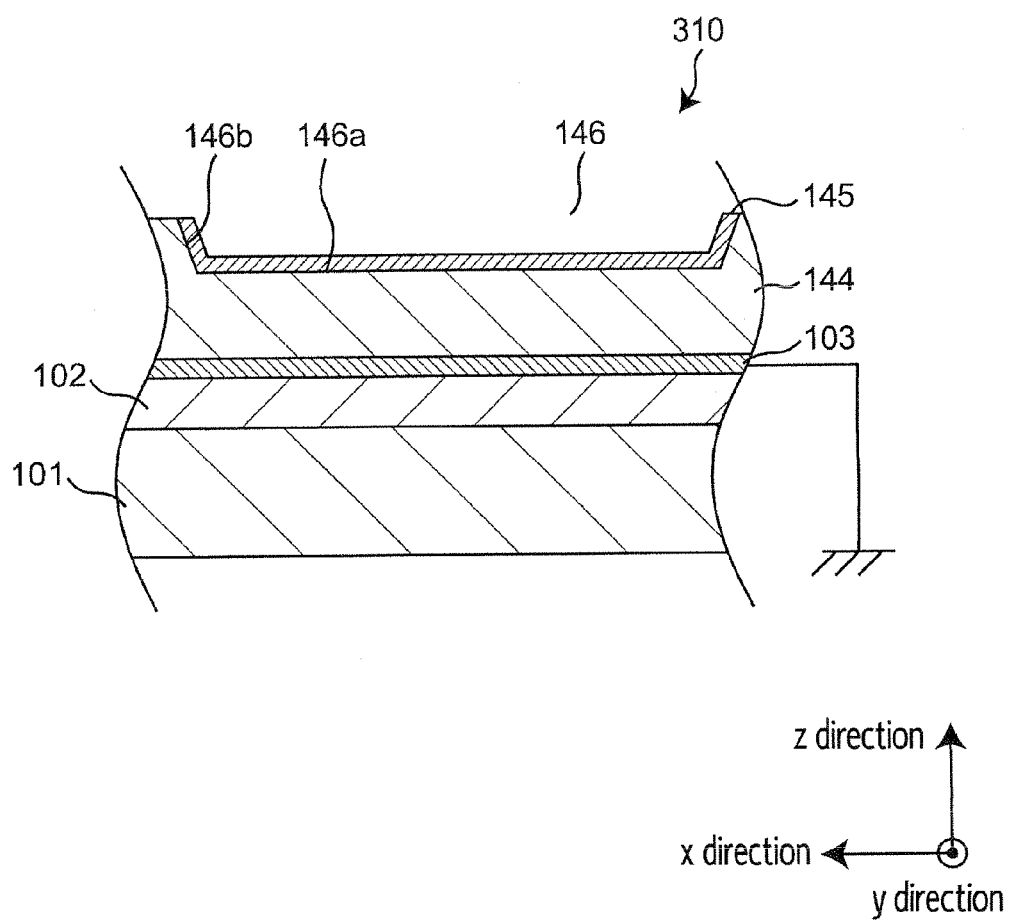


Fig. 6

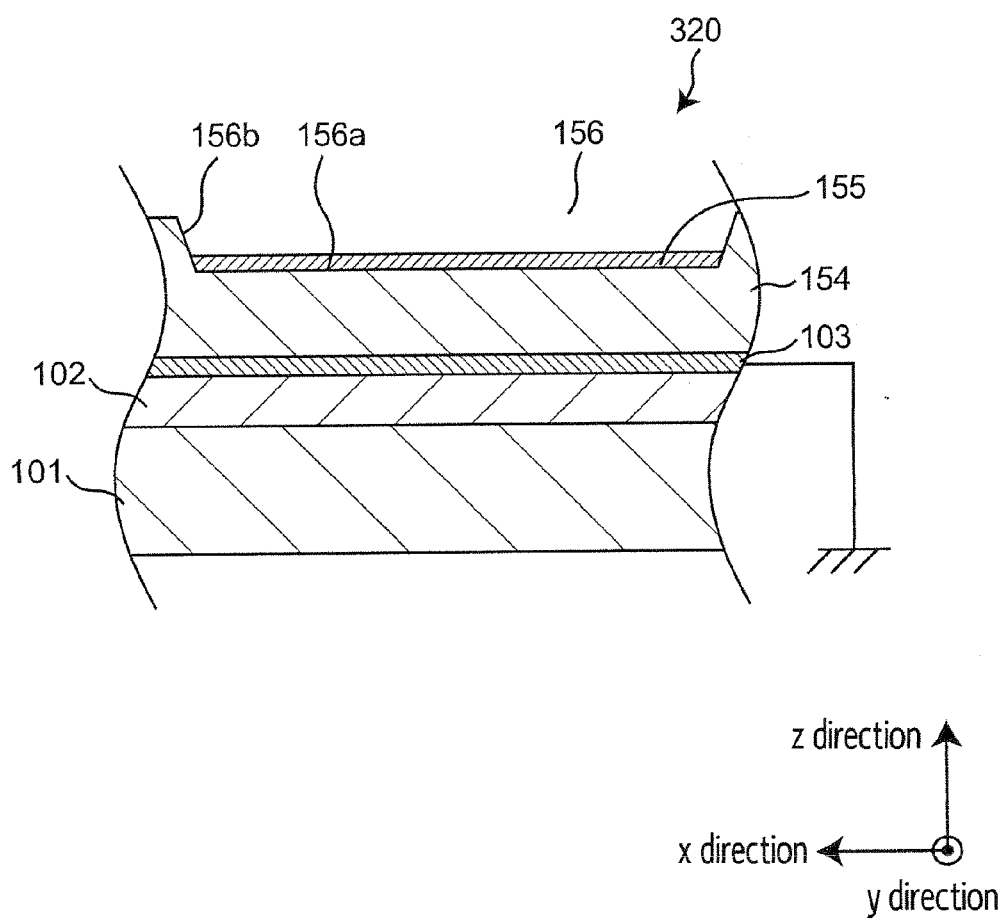


Fig. 7

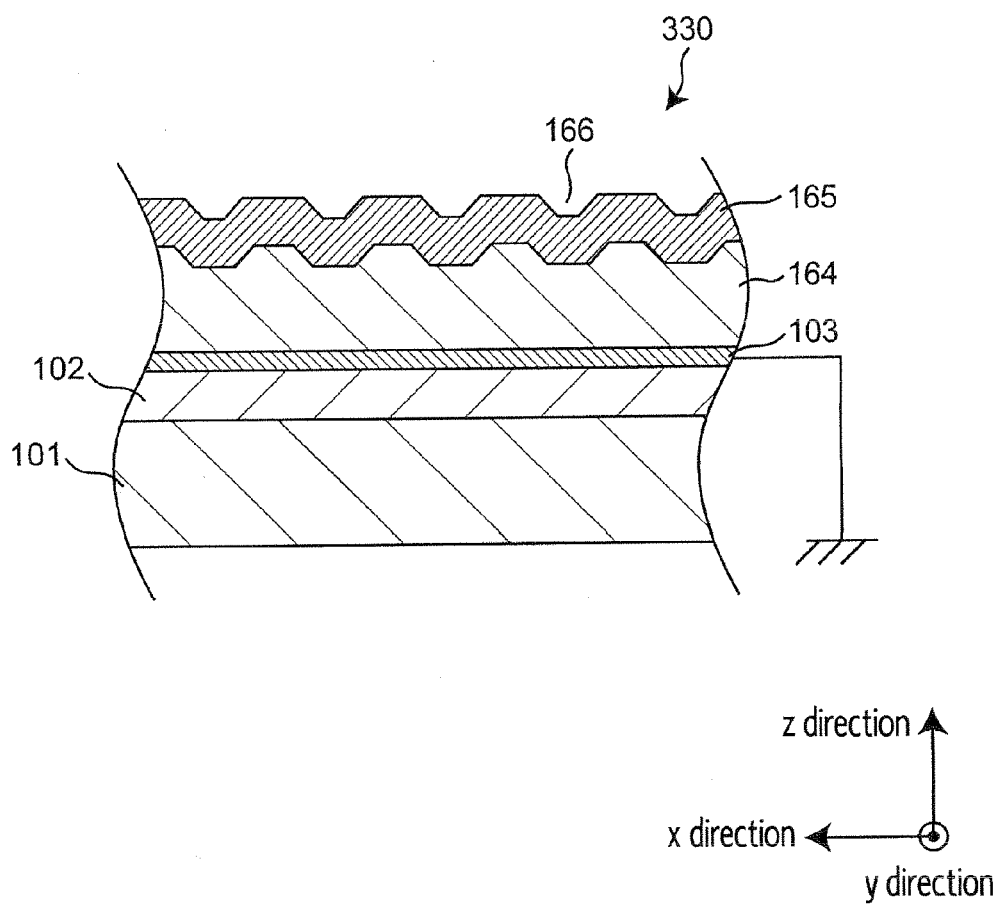


Fig. 8

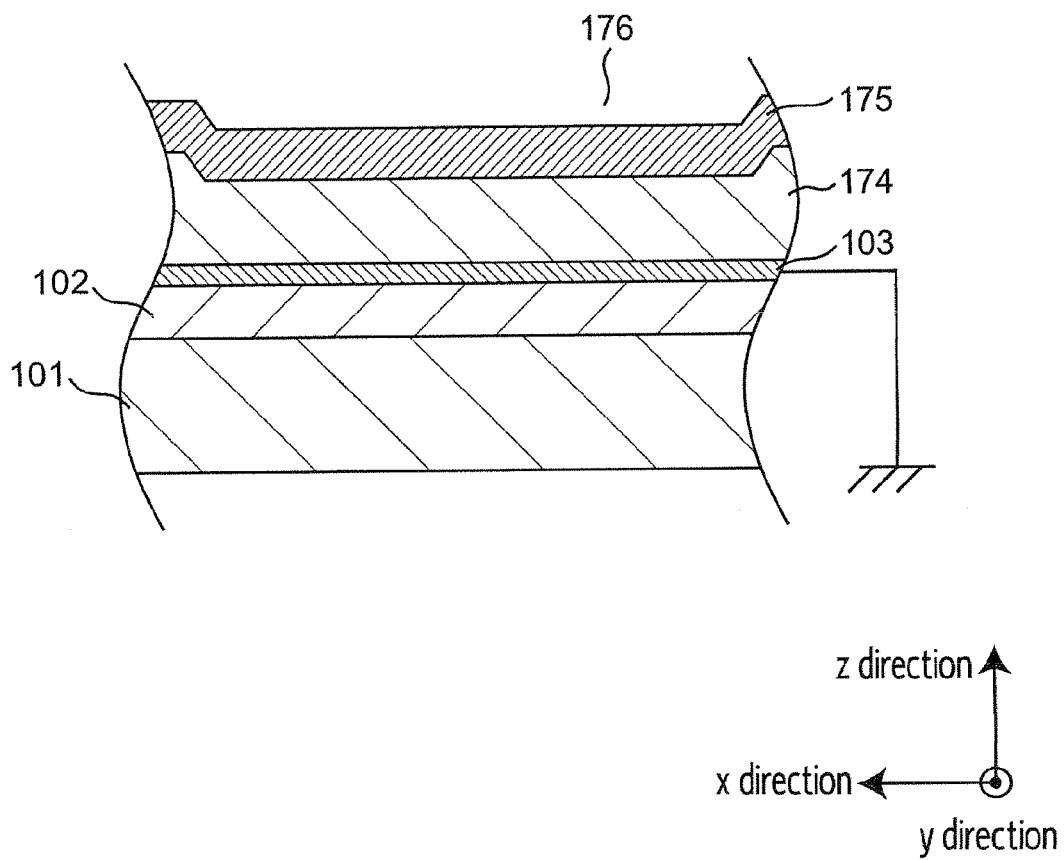


Fig. 9

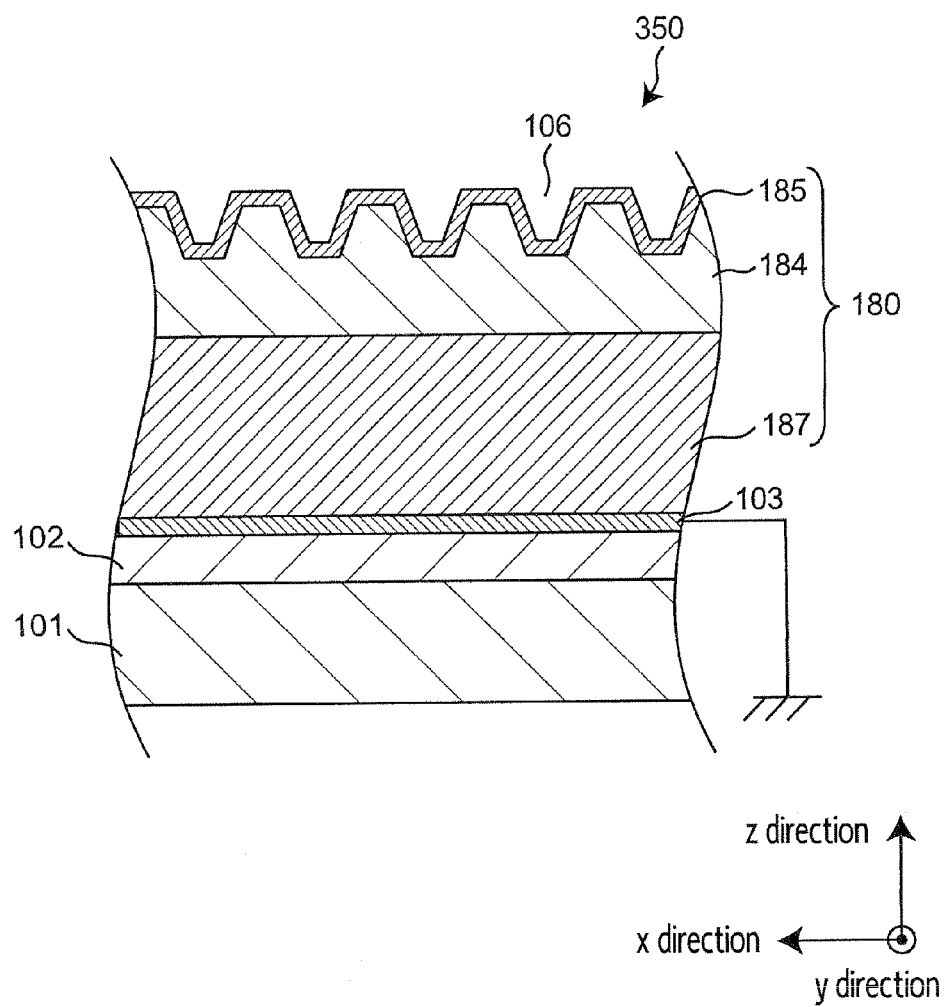


Fig. 10

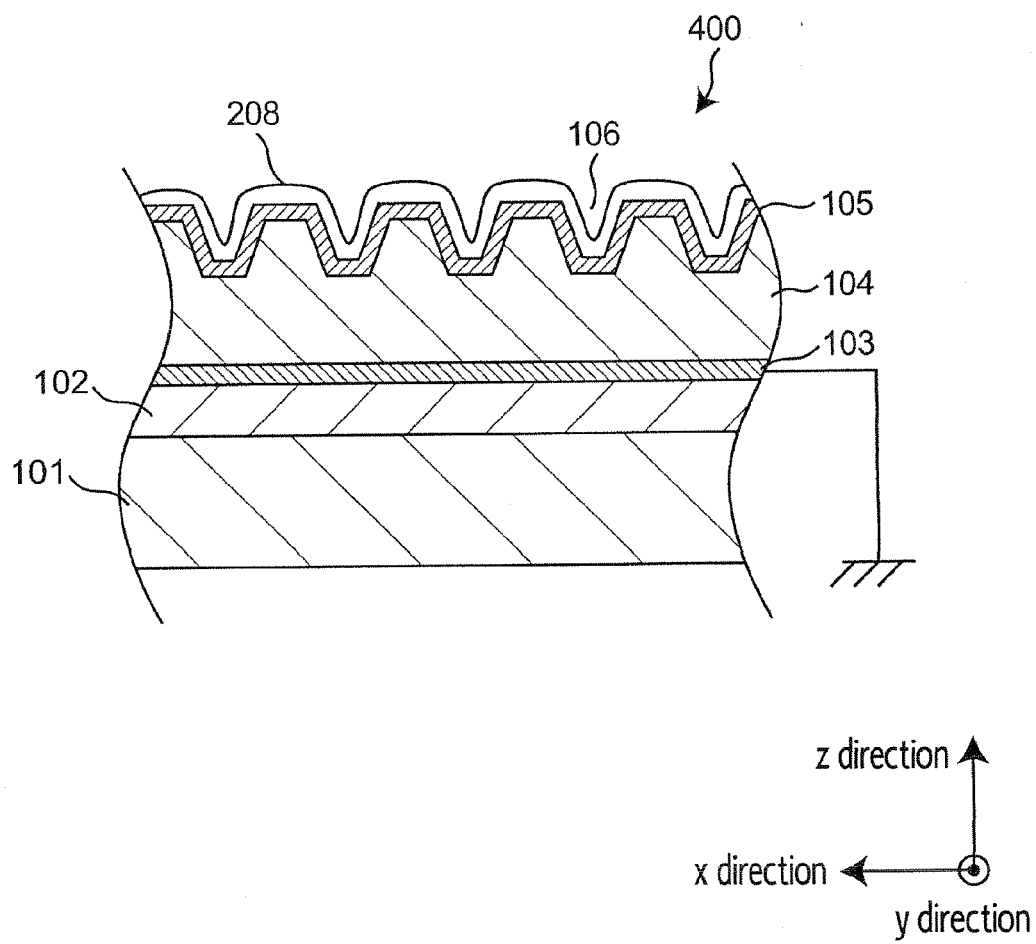


Fig. 11

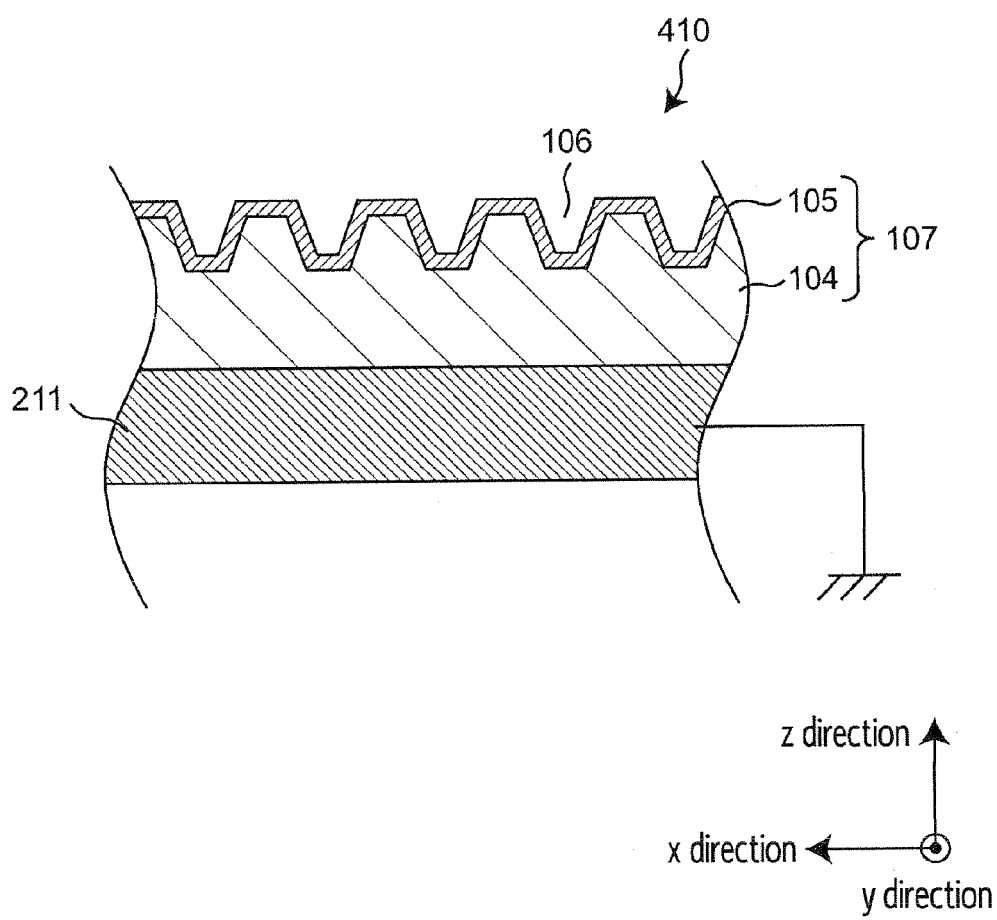


Fig. 12

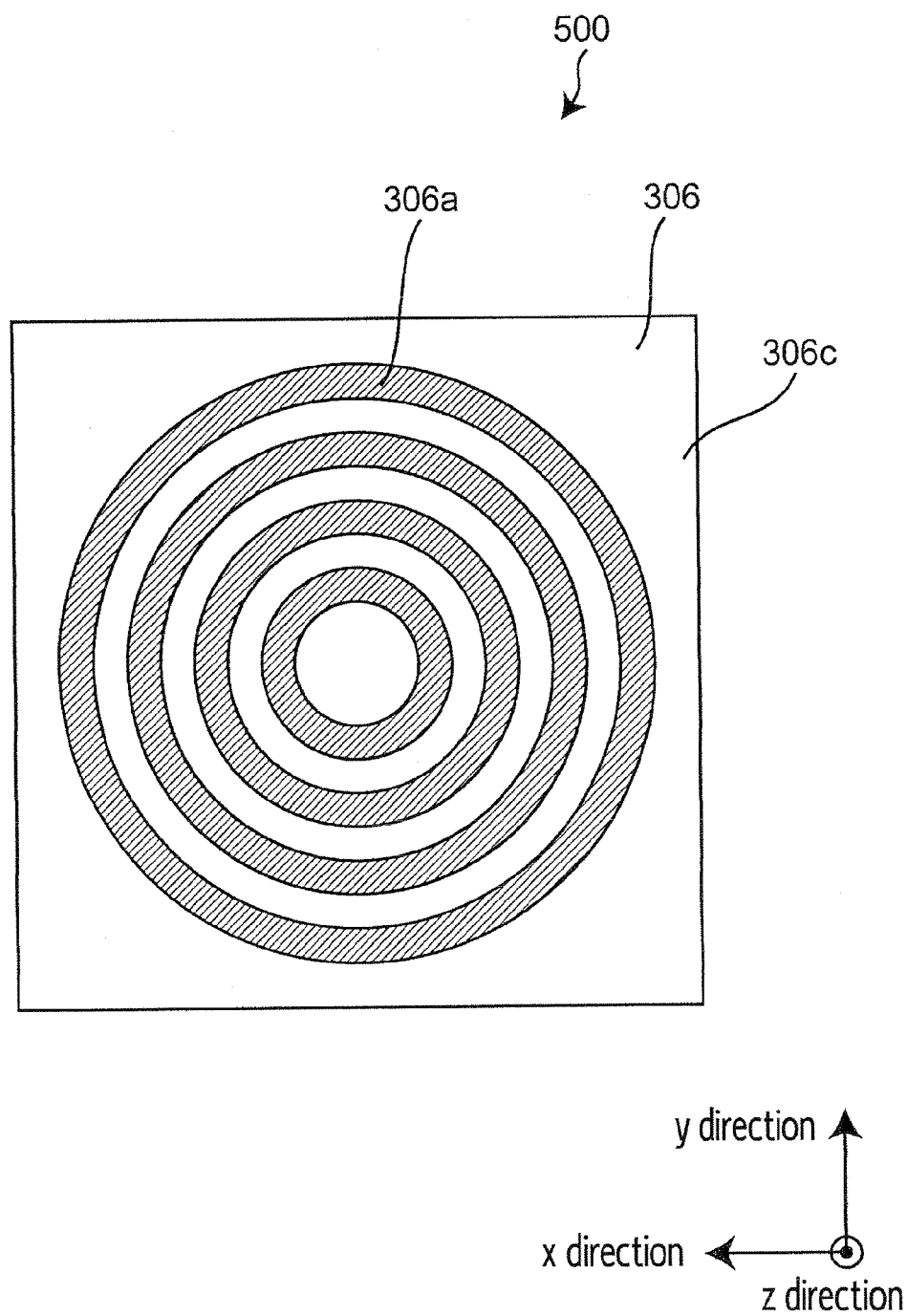


Fig. 13

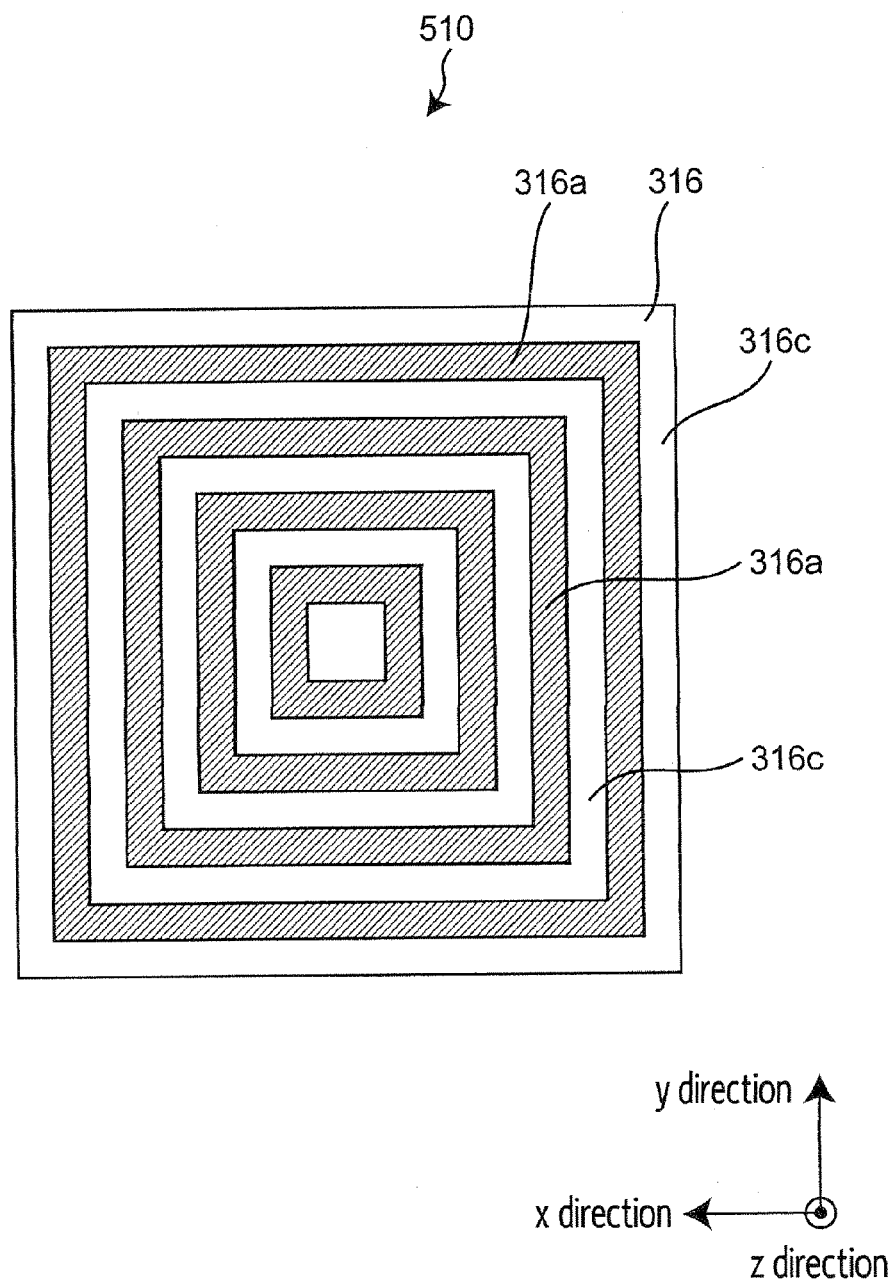


Fig. 14

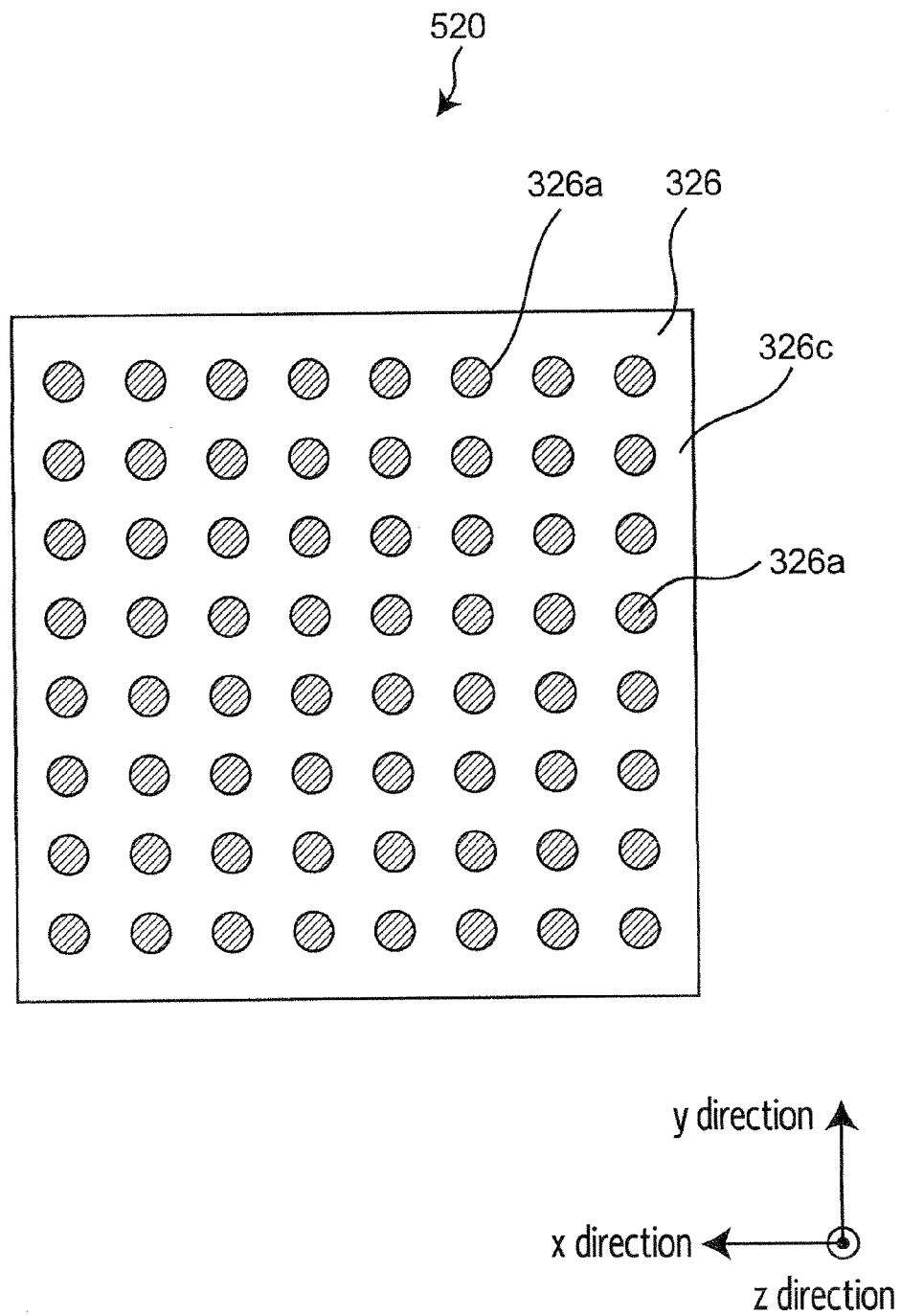


Fig. 15

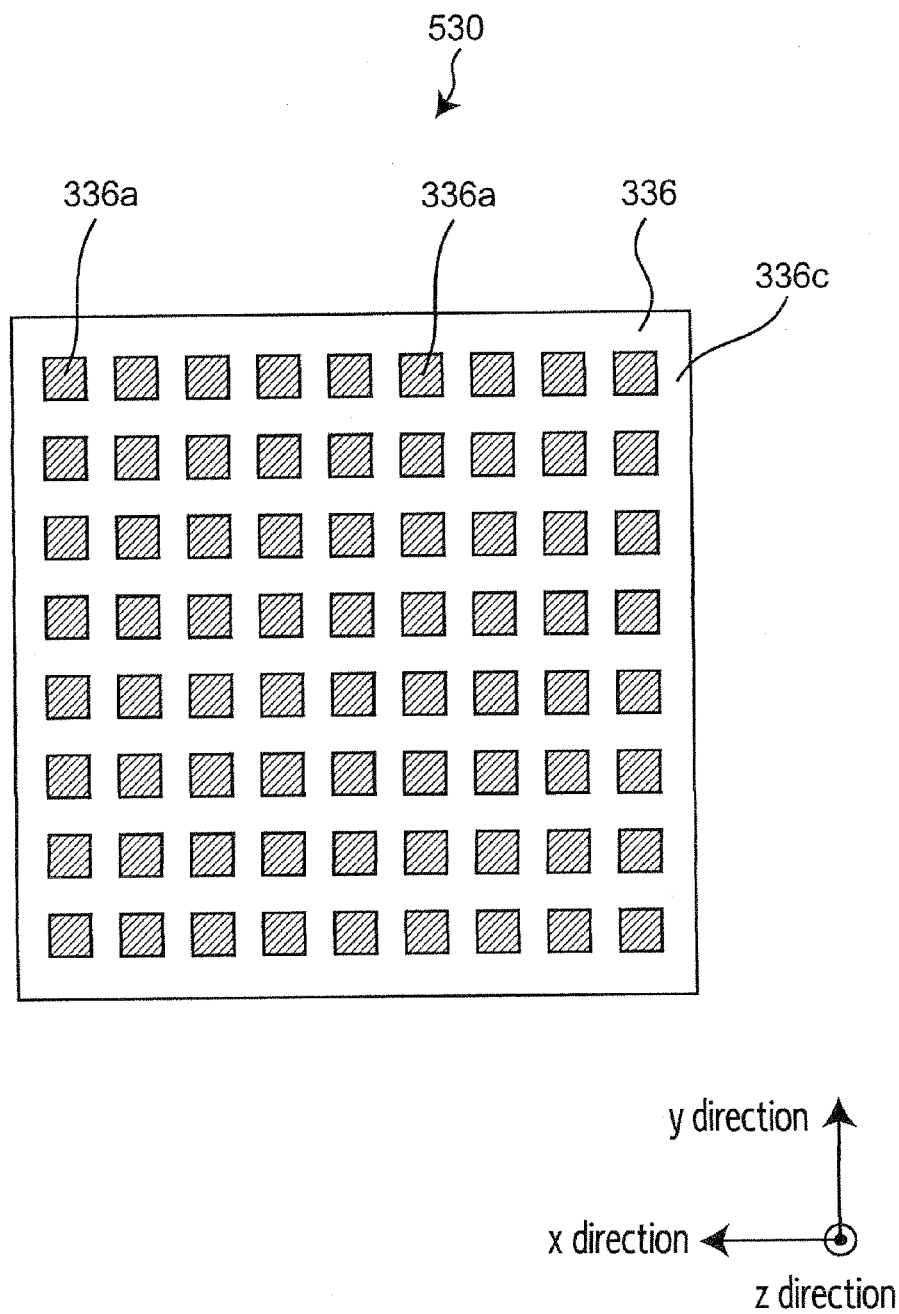


Fig. 16

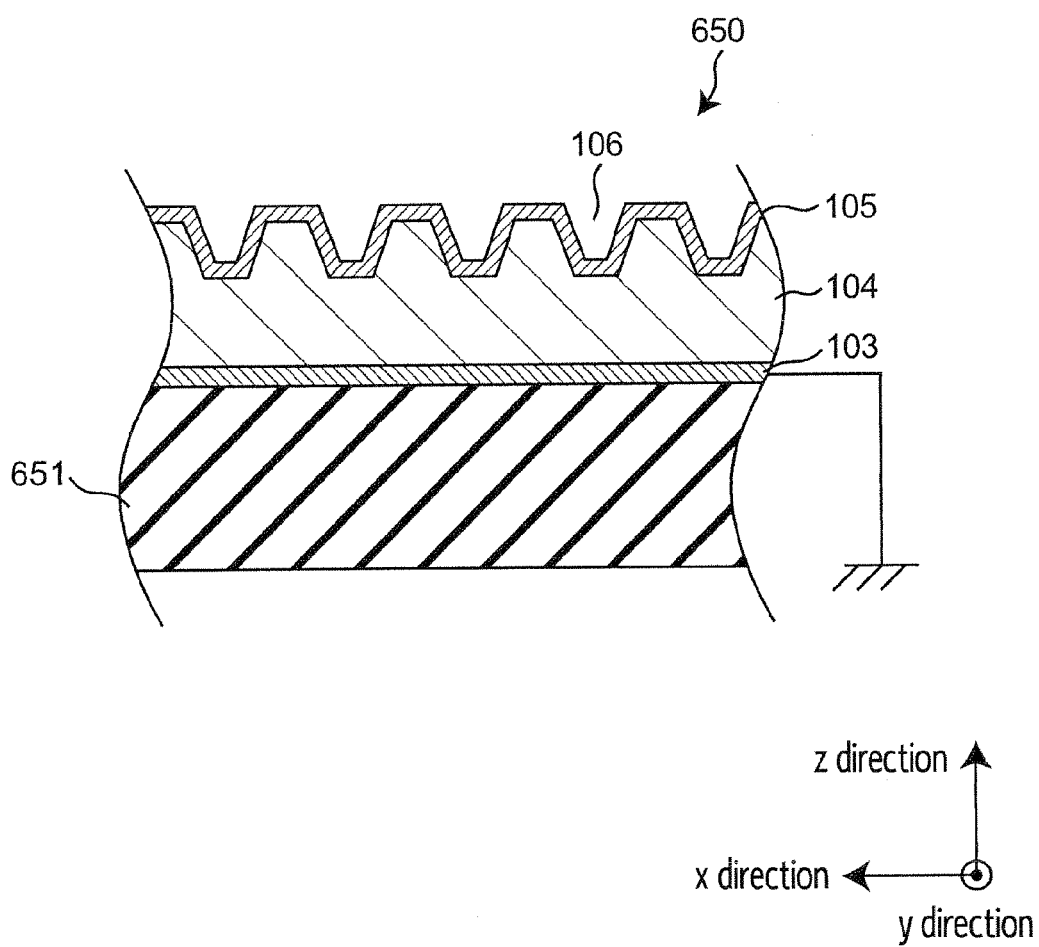


Fig. 17

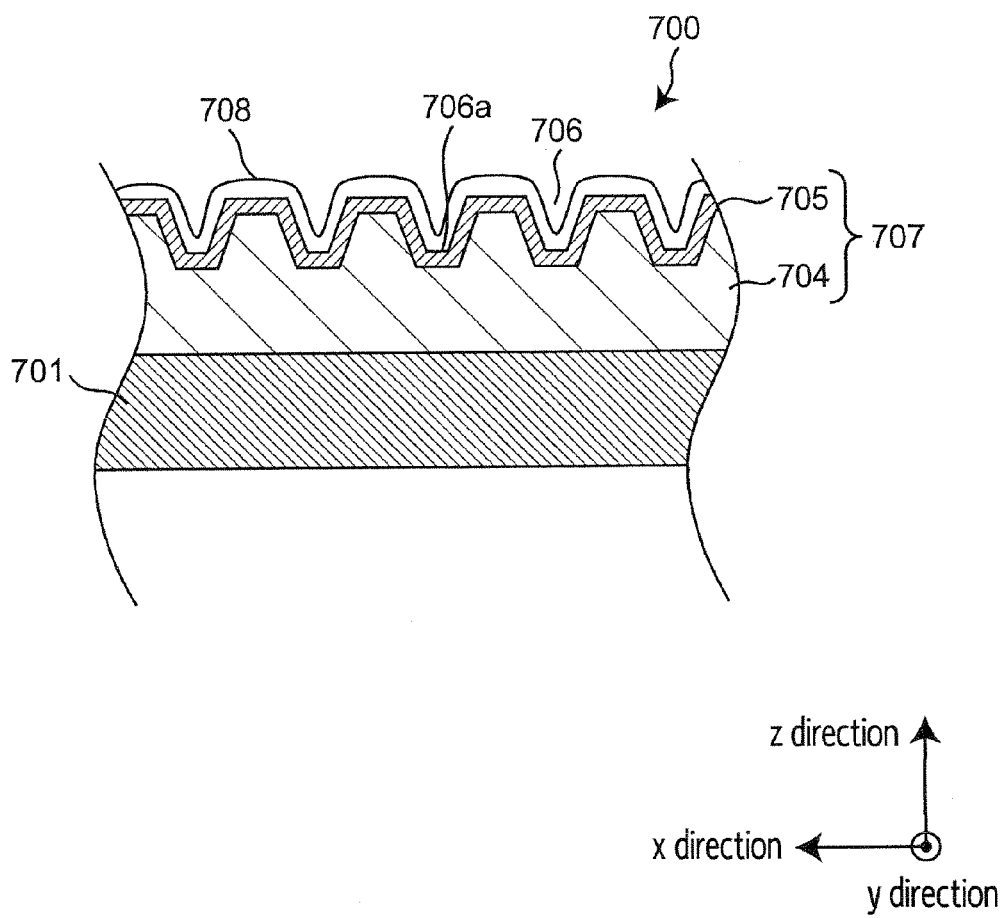


Fig. 18

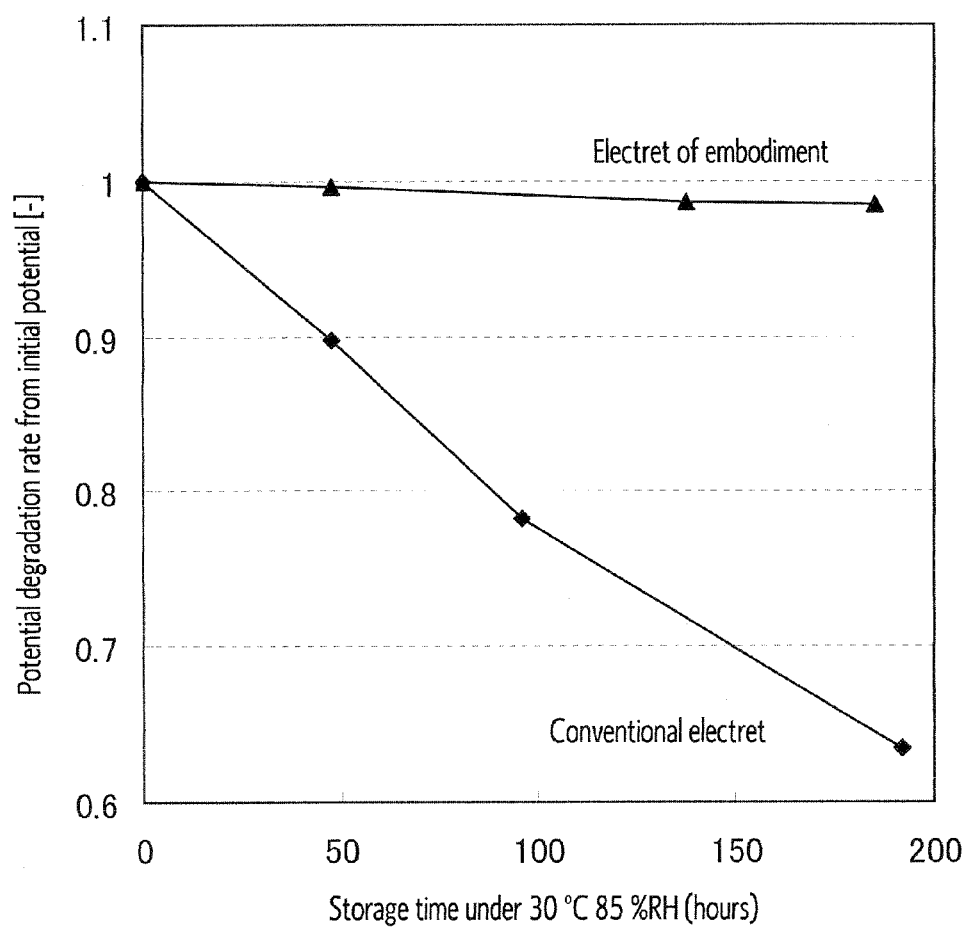


Fig. 19

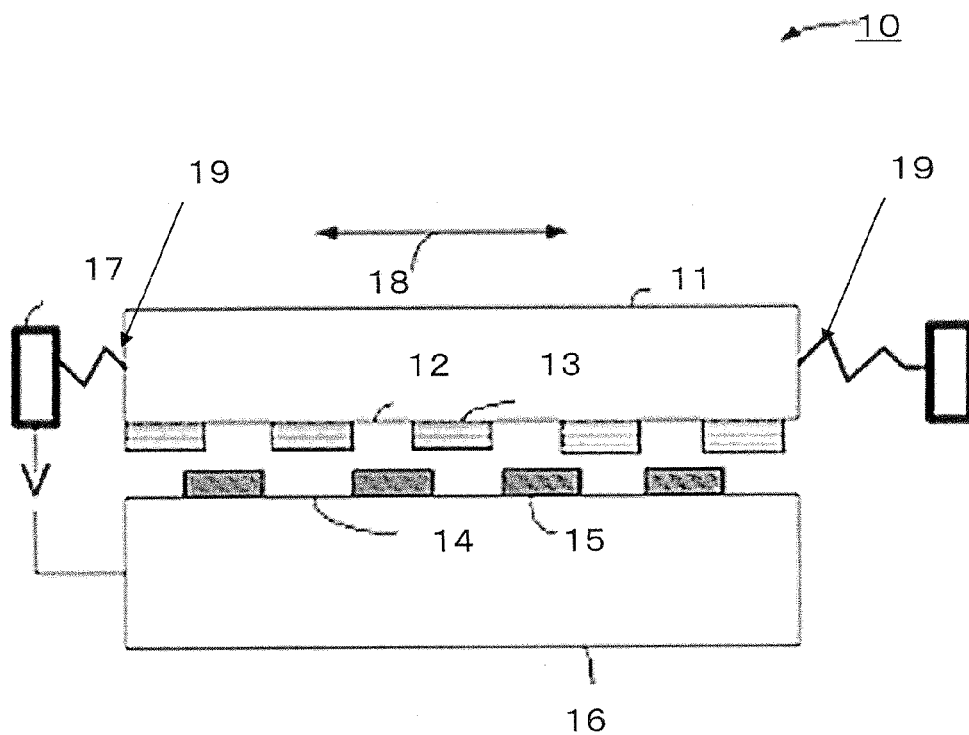


Fig. 20

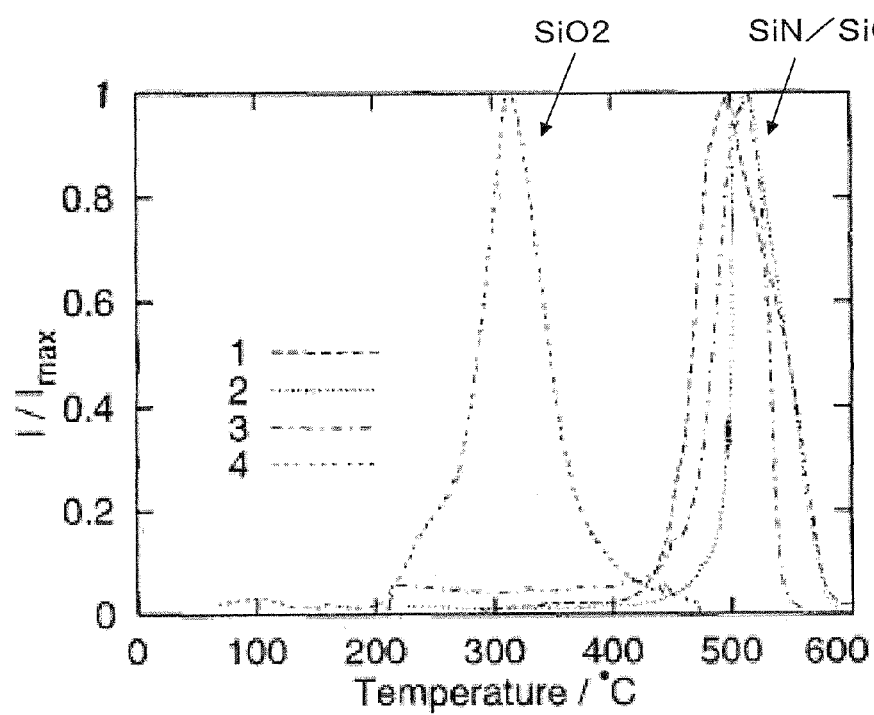


Fig. 21

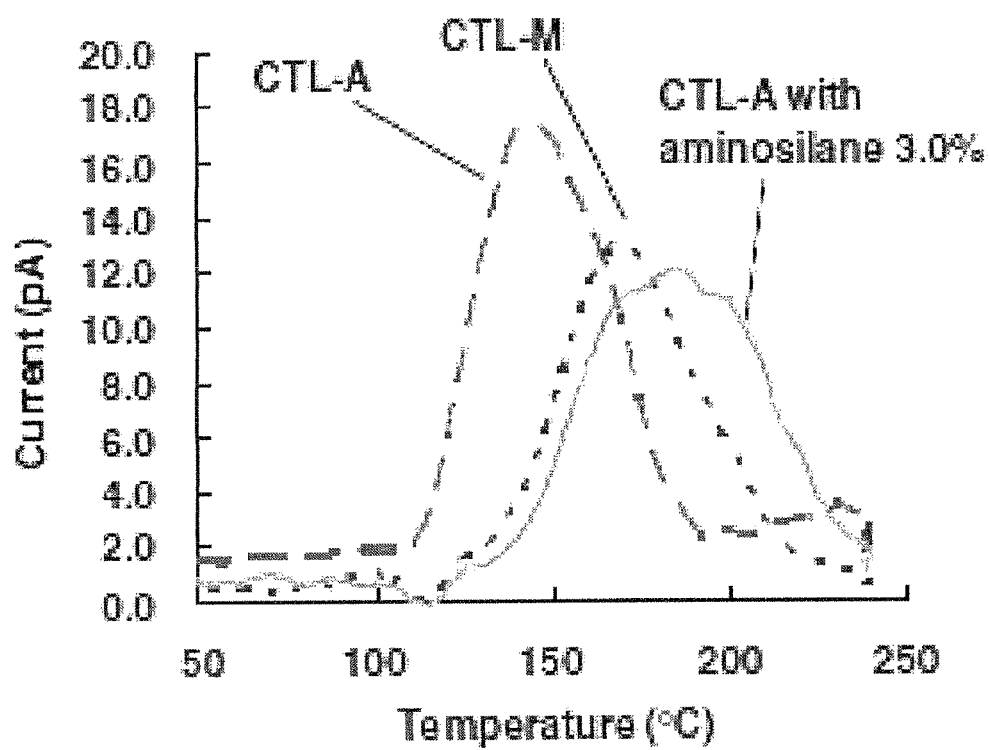


Fig. 22

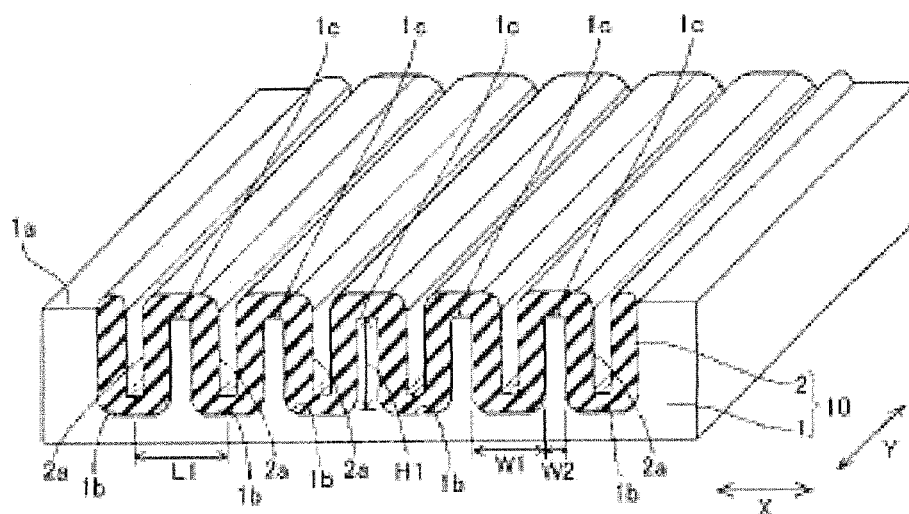
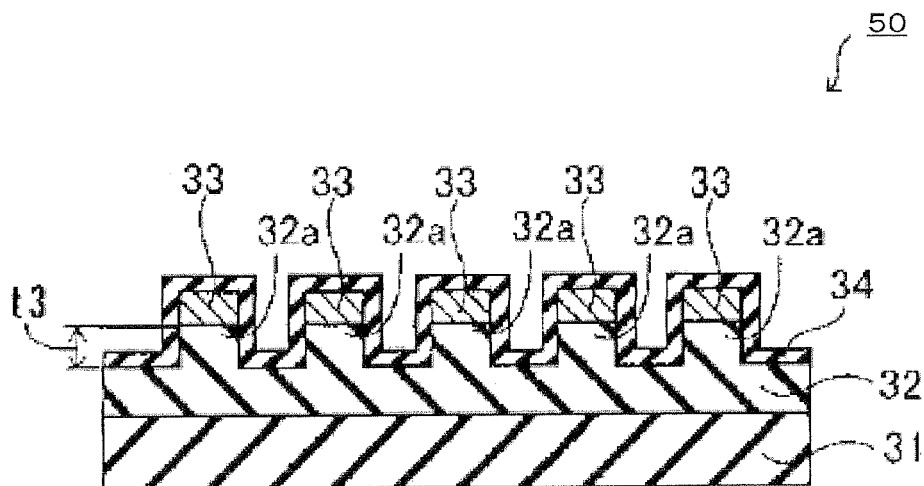


Fig. 23



1

ELECTRET ELEMENT AND VIBRATION POWER GENERATING DEVICE USING THE SAME

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the priority of Japanese Patent Application No. 2012-257364 filed on Nov. 26, 2012, the disclosure of which, including the specification, drawings, and claims, are incorporated herein by reference in their entireties.

TECHNICAL FIELD

The present invention is related to an electret element and a vibration power generating device provided with the electret element.

BACKGROUND OF THE INVENTION

A vibration power generating device for converting vibration energy to electric energy has been proposed, which uses an electret which is a dielectric holding electrical charge semipermanently, and employs electrostatic induction occurred in a conductor which is approaching to the electret.

FIG. 19 shows a schematic cross-sectional view of a vibration power generating device described in JP-A 2005-529574. This vibration power generating device consists of a first substrate 11 provided with a plurality of collector electrodes 13, a second substrate 16 provided with a plurality of electret elements 15. The first substrate 11 and the second substrate 16 are arranged with a predetermined gap therebetween. The second substrate 16 is fixed. A spring 19 is connected to each of side surfaces of the first substrate 19 and to a fixing structure 17. The first substrate 11 is moved laterally by external vibration and returned to a fixed-position by spring force of the spring 19. This movement causes increase and decrease in overlapped area of the electret element 15 and the collector electrode 13 opposed to the element, changing the electrical charges induced in the collector electrode 13. An electrostatic induction-type vibration power generation device produces power by taking out the change in electrical charge as the electric energy.

H. Amjadi proposed an inorganic electret consisting of a laminate of a silicon nitride film and a silicon oxide film in "Charge Storage in Double Layers of Thermally Grown Silicon Dioxide and APCVD Silicon Nitride" (IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 6, No. 6, December 1999). Sakane et al, proposed an organic electret of a perfluoride polymer in "The development of a high-performance perfluorinated polymer electret and its application to micro power generation" (JOURNAL OF MICROMECHANICS AND MICROENGINEERING 18 (2008) 104011). FIG. 20 shows the measurement results of TSC (Thermal Stimulated Current) of the inorganic electret proposed by H. Amjadi. FIG. 21 shows the TSC measurement results of the organic electret proposed by Sakane et al. The TSC measurement is technique of detecting electric current discharged when an object is heated to raise a temperature of the object. As the temperature at which the electric current is discharged from the object is higher, the thermal resistance of the object is higher. A TSC peak temperature for the inorganic electret consisting of a laminate of a silicon nitride film and a silicon oxide film is about 500° C. and the TSC peak temperature for CTL-A with aminosilane 3.0% as the organic electret is about 190° C.

2

The electret consisting of the laminate of the silicon nitride film and the silicon oxide film has high reliability under high-temperature environment since the electret has high thermal resistance.

FIG. 22 is a cross-sectional view of an electret element 10 described in JP-A 2008-141171. The electret element 10 consists of a silicon substrate 1 and a silicon oxide film 2. Groove portions 1b and protruded portions 1c are formed in the silicon substrate 1 and the silicon oxide film 2 is formed to cover the inner surfaces of the groove portions 1b and the surfaces of the protruded portions 1c between the groove portions 1b. In the case where the silicon oxide film 2 is formed by thermal oxidation method, the silicon oxide film 2 can be formed not only in a direction perpendicular to a principal surface 1a of the silicon substrate 1, but also in a direction parallel to the principal surface 1a of the silicon substrate 1 from the inner side surface of the groove portion 1b. Therefore, the formation of the silicon oxide film 2 of which surface area (volume) per unit planar volume is increased, can increase an amount of electrical charge which can be injected to the electret element 10, thereby increasing surface potential. The use of such an electret element can increase power output of the vibration power generation device.

FIG. 23 is a cross-sectional view of a fixed electrode portion 50 including an electret element, which is described in WO2008/053794. An electret film 32 having convex portions 32a is formed on a surface of an electret film 31 and a pectinated conductor layer 33 is formed on a surface of the electret film 32 (the convex portions 32a). A film 34 for preventing electrical charge from flowing out is formed on the side surface and the upper surface of the conductor layer 33. Since the conductor layer 33 functions to block electric field formed by the electrical charge accumulated in the electret film 32, the surface potential of a region where the conductor layer 33 is formed is small and the surface potential of the region where the conductor layer 33 is not formed and the electret film 32 is exposed is large. In this manner, the high and low surface potentials are formed like a comb in the fixed electrode portion 50 including electret element. Therefore, when the overlapped area of the fixed electrode portion 50 and the collector electrode opposed thereto is changed during the operation, an amount of electrical charge induced in the collector electrode is changed and the change is taken out as the electric current.

SUMMARY OF THE INVENTION

The object of the present invention to provide an electret element wherein electrical charge-holding stability of an electret including a laminate of two dielectrics is improved, and the electrical charge is particularly prevented from flowing out to the environment around a substrate.

An embodiment of the present invention is an electret element including a substrate, an electrically-conductive electrode, and an electret layer including a first dielectric layer and a second dielectric layer, wherein:

the electret layer is capable of holding electrical charge, the electrically-conductive electrode is formed on a surface of the substrate,

the first dielectric layer is formed on a surface of the electrically-conductive electrode and has, in a surface opposite to an electrically-conductive electrode-side surface, at least one concave portion having a bottom face, a side wall and a top face,

the second dielectric layer covers the entire of the bottom face and at least a part of the side wall, and

3

a bottom E_c of conductive band of the second dielectric layer is lower than a bottom E_c of conductive band of the first dielectric layer, or a top E_v of valence band of the second dielectric layer is higher than a top E_v of valence band of the first dielectric layer.

The electret element according to one embodiment of the present invention can improve the electrical charge-holding stability of the electret which is a laminate of two dielectrics, and can particularly prevent the electrical charge from flowing out to the environment of the substrate. Therefore, the use of the electret element according to one embodiment of the present invention can provide a vibration power generating device which is excellent in stability of power output.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of an electret element 100 according to an embodiment.

FIG. 2 is a plan view of the electret element 100 according to the embodiment.

FIG. 3 is a cross-sectional view of a vibration power generating device using the electret element 100 according to the embodiment.

FIG. 4 is a cross-sectional view of a first variation of the electret element according to the embodiment.

FIG. 5 is a cross-sectional view of a second variation of the electret element according to the embodiment.

FIG. 6 is a cross-sectional view of a third variation of the electret element according to the embodiment.

FIG. 7 is a cross-sectional view of a fourth variation of the electret element according to the embodiment.

FIG. 8 is a cross-sectional view of a fifth variation of the electret element according to the embodiment.

FIG. 9 is a cross-sectional view of a sixth variation of the electret element according to the embodiment.

FIG. 10 is a cross-sectional view of seventh variation of the electret element according to the embodiment.

FIG. 11 is a cross-sectional view of an eighth variation of the electret element according to the embodiment.

FIG. 12 is a plan view of a first dielectric layer of a ninth variation of the electret element according to the embodiment.

FIG. 13 is a plan view of a first dielectric layer of a tenth variation of the electret element according to the embodiment.

FIG. 14 is a plan view of a first dielectric layer of an eleventh variation of the electret element according to the embodiment.

FIG. 15 is a plan view of a first dielectric layer of a twelfth variation of the electret element according to the embodiment.

FIG. 16 is a cross-sectional view of a thirteenth variation of the electret element according to the embodiment.

FIG. 17 is a cross-sectional view of an example of the electret element.

FIG. 18 is a graph showing potential degradation with time of an example in environment of high humidity (30° C. and 85% RH).

FIG. 19 is a cross-sectional view of a conventional vibration power generating device.

FIG. 20 is a graph showing TSC measurement results of a conventional inorganic electret consisting of a laminate of a silicon nitride film and a silicon oxide film.

FIG. 21 is a graph showing TSC measurement results of a conventional organic electret.

4

FIG. 22 is a perspective view of a conventional electret element consisting of a silicon substrate with concavo-convex structure and a silicon oxide film formed to cover the concavo-convex structure.

FIG. 23 is a cross-sectional view of a fixed electrode portion of a conventional electrostatic induction-type power generating device.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Circumstances where an Embodiment of the Present Invention was Obtained

As described above, the electret including a laminate of a silicon nitride film and a silicon oxide film has high thermal resistance and is advantageous to the use under environment of high temperature. However, insulation characteristics between the silicon nitride film and the silicon oxide film are relatively low since there congested defects due to the lattice mismatch and the difference in stress between the two films. For this reason, the electrical charge tends to move along the interface and the moved electrical charge tends to finally flow out from the interface exposed at the end face and so on.

Further, only the silicon oxide film 2 is formed as the electret film in the electret element 40 shown in JP-A 2008-141171. If a silicon nitride film is formed on a surface of this silicon oxide film 2, it is considered that a laminate structure described in "Charge Storage in Double Layers of Thermally Grown Silicon Dioxide and APCVD Silicon Nitride" (H. Amjadi, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 6, No. 6, December 1999) would be obtained and the thermal resistance would be improved. However, in such a laminate structure, the electrical charge tends to move at the interface between the silicon nitride film and the silicon oxide film, whereby the electrical charge tends to flow out from the exposed interface.

Further, it is considered that, if the film 34 for preventing electrical charge from flowing out is the silicon nitride film in the fixed electrode portion 50 including the electret element described in WO2008/053794, the thermal resistance would be improved. However, the electrical charge tends to move at the interface between the silicon nitride film and the silicon oxide film and thereby tends to flow out from the exposed interface. Further, the electrical charge tends to flow out to the conductor layer 33 since the conductor layer 33 pulls the electrical charge.

As described above, the electret including the laminate of the silicon nitride film and the silicon oxide film shows favorable thermal resistance since the electrical charge held by the electret are difficult to be discharged, but the long-term electrical charge-holding stability is not satisfactory. For this reason, there is a problem that the power output gradually decreases with time in a vibration power generating device provided with an electret element including the electret of this laminate.

The present inventors studied a construction for preventing the electrical charge from flowing out due to the movement of the charge at the interface, and improving the electrical charge-holding stability in the electret including the laminate of the silicon nitride film and the silicon oxide film. As a result, the present inventors found that the electrical charge-holding stability is improved by forming concave portion in the silicon oxide film and laying the silicon nitride film on the silicon oxide film such that the

silicon nitride film covers the entire of bottom face and at least a part of side wall of the concave portion.

MODES OF THE INVENTION

A first mode of the present invention is an electret element including a substrate, an electrically-conductive electrode, and an electret layer including a first dielectric layer and a second dielectric layer, wherein:

the electret layer is capable of holding electrical charge,

the electrically-conductive electrode is formed on a surface of the substrate,

the first dielectric layer is formed on a surface of the electrically-conductive electrode and has, in a surface opposite to an electrically-conductive electrode-side surface, at least one concave portion having a bottom face, a side wall and a top face,

the second dielectric layer covers the entire of the bottom face and at least a part of the side wall, and

a bottom E_c of conductive band of the second dielectric layer is lower than a bottom E_c of conductive band of the first dielectric layer, or a top E_v of valence band of the second dielectric layer is higher than a top E_v of valence band of the first dielectric layer.

Here, the "electret" means a dielectric which is capable of holding electrical charge semipermanently and the "electret layer" means a layer of electret. The "electret element" means an element including a substrate which supports the electret (or the electret layer) and an electrode and so on. The electret (or the electret layer) may consist of a plurality of dielectrics and the electrical charge may be held by a part or all of the plural dielectrics.

In the first mode, the electrical charge held at the bonded interface between the first dielectric layer and the second dielectric layer is pulled toward the electrically-conductive electrode by electrostatic force and therefore cannot move in a direction away from the electrically-conductive electrode ("z" direction in FIG. 1). More specifically, even if the electrical charge tries to move along the side wall of the concave portion at the interface between the first dielectric layer and the second dielectric layer, it is pulled toward the electrically-conductive electrode and difficult move in a direction away from the electrically-conductive electrode. As a result, the electrical charge is stably held in a bottom region of the concave portion.

In the first mode, when the electrical charge held by the electret layer is negative charge, a bottom E_c of conductive band of the second dielectric layer is lower than a bottom E_c of conductive band of the first dielectric layer. When the electrical charge held by the electret layer is positive charge, a top E_v of valence band of the second dielectric layer is higher than a top E_v of valence band of the first dielectric layer. By satisfying this relationship, the electret element with high thermal resistance can be obtained wherein the electrical charge is less likely to be discharged from the electret layer even under high temperature.

A second mode is the electret element according to the first mode, wherein the electret layer further includes at least one dielectric layer and the at least one dielectric layer is formed between the electrically-conductive electrode and the first dielectric layer. In this case, an amount of the electrical charge held in the electret element is increased, whereby a surface potential can be increased.

A third mode is the electret element according to the first or the second mode, wherein the electrical charge is held in the electret layer and the electrically-conductive electrode is connected to:

a potential which is of the same polarity as that of the electrical charge and has an absolute value being smaller than the absolute value of a surface potential of the electret layer, or

a potential which is of a polarity different from that of the electrical charge.

A fourth mode is the electret element according to the first or the second mode, wherein the electrically-conductive electrode is connected to an earth potential.

When the electrically-conductive electrode is connected to: the earth potential; or the potential which is of the same polarity as that of the electrical charge and has an absolute value being smaller than the absolute value of a surface potential of the electret layer; or the potential which is of a polarity different from that of the electrical charge, the electrical charge is more surely pulled toward the electrically-conductive electrode by electrostatic force. As a result, the electrical charge is more difficult to move in a direction away from the electrically-conductive electrode ("z" direction in FIG. 1), and held more stably in the bottom region of the concave portion.

A fifth mode is the electret element according to any one of the first to the fourth modes, wherein the first dielectric layer is a silicon oxide film and the second dielectric layer is a film selected from the group consisting of a silicon nitride film, an aluminum oxide film, a hafnium oxide film and a titanium oxide film.

A sixth mode is the electret element according to any one of the first to the fifth modes, wherein the substrate is an electrically-conductive substrate and a third dielectric layer is formed between the electrically-conductive substrate and the electrically-conductive electrode.

A seventh mode is the electret element according to the sixth mode, wherein the electrically-conductive substrate is a silicon substrate, the third dielectric layer is a silicon oxide film and the electrically-conductive electrode consists of polycrystalline silicon.

An eighth mode is the electret element according to any one of the first to the fifth modes, wherein the substrate is an insulative substrate.

A ninth mode is the electret element according to the eighth mode, wherein the insulative substrate is a glass substrate or a sapphire substrate, and the electrically-conductive electrode consists of a material selected from the group consisting of polycrystalline silicon, aluminum and copper.

A tenth mode is the electret element according to the first or the second element wherein an electrically-conductive substrate is substituted for the substrate and the electrically-conductive electrode, and the first dielectric layer is formed on a surface of the electrically-conductive substrate. In this case, it is not necessary to form the electrically-conductive electrode, and thereby the number of times of membrane formation.

An eleventh mode is the electret element according to the tenth electret element, wherein the electrical charge is held in the electret layer and the electrically-conductive substrate is connected to:

a potential which is of the same polarity as that of the electrical charge and has an absolute value being smaller than the absolute value of a surface potential of the electret layer, or

a potential which is of a polarity different from that of the electrical charge.

A twelfth mode is the electret element according to the tenth mode wherein the electrically-conductive substrate is connected to an earth potential. The effects of connecting the electrically-conductive substrate to any one of the above-

mentioned potentials in the eleventh and the twelfth modes are the same as those of the third and the fourth modes.

A thirteenth mode is the electret element according to any one of the first to the twelfth modes, wherein a depth from the bottom face to the top face of the concave portion is larger than a thickness of the second dielectric layer. In this case, it is possible to prevent the outflow of not only the electrical charge which moves at the interface between the first dielectric layer and the second dielectric layer, but also the electrical charge which moves inside the second dielectric layer.

A fourteenth mode is the electret element according to any one of the first to the thirteenth modes, wherein a plurality of the concave portions are formed and an interval between two adjacent concave portions is larger than a thickness of the first dielectric layer.

A fifteenth mode is the electret element according to any one of the first to the fourteenth modes further including a moisture-proof layer, wherein the moisture-proof layer covers:

- a surface of the second dielectric layer, or
- the surface of the second dielectric layer and a region of the surface of the first dielectric layer, which region is not covered with the second dielectric layer.

A sixteenth mode is a vibration power generating device which is provided with the electret element according to any one of the first to the fifteenth modes. As described above, since the electrical charge-holding stability can be improved in the electret element according to the first mode, the vibration power generating device utilizing the electret element of the first mode or another electret element which utilizes the first mode, can improve the power output.

Embodiments of the present invention will be described below with reference to the drawings. In the following description, redundant description for substantially the same constitution may be omitted.

Embodiments

FIG. 1 is a cross-sectional view of an electret element 100 of an embodiment. FIG. 2 is a plan view of the electret element 100 and the cross-sectional view shown in FIG. 1 corresponds to the cross section taken along A-B in FIG. 2. The electret element 100 consists of a substrate 101, a third dielectric layer 102 formed on a principal surface of the substrate 101, an electrically-conductive electrode 103 formed on a surface of the third dielectric layer 102, a first dielectric layer 104 formed on a surface of the electrically-conductive electrode 103 and a second dielectric layer 105.

A laminate of the first dielectric layer 104 and the second dielectric layer 105 constitutes an electret layer 107 and electrical charge is injected in the electret layer 107. In this embodiment, a plurality of concave portions 106 are formed in the first dielectric layer 104 and the second dielectric layer 105 is formed such that it covers the concave portions 106, that is, it covers the entire of the bottom face 106a, the side wall 106b and the top face 106c.

The concave portion 106 has the bottom face 106a, the side wall 106b, and the top face 106c. In the illustrated embodiment, the bottom face 106a and the top face 106c of the concave portion are parallel to a principal surface of the substrate 101. For example, the bottom face 106a and the top face 106c may be curved partially. The side wall 106b may be vertical to the principal surface of the substrate 101 or may be inclined as shown in FIG. 1. When the side wall 106b is inclined, it is easy to form the second dielectric layer 105 uniformly. Alternatively, the side wall 106b may be

curved. For example, the side wall 106 may be a quadratic curve represented by $f(x)=x^2$ in the cross section shown in FIG. 1.

A depth from the bottom face 106a to the top face 106c of the concave portion 106 is larger than a thickness of the second dielectric layer 105. When the bottom face 106a of the concave portion is curved and the level (height) of the bottom face is not constant, the deepest point (a point which is closest to the substrate 101) is a basis for determining the depth. When the top face 106c is curved and the level (height) of the top face is not constant, the highest point (a point which is furthest from the substrate 101) is the basis for determining the depth. The effects obtained when the depth of the concave portion 106 and the thickness of the second dielectric layer 105 satisfy this relationship are as described in connection with the eleventh mode.

As shown in FIG. 2, the concave portions 106 are of a rectangular shape when viewed in "z" direction and are juxtaposed parallel to each other. Since FIG. 2 is a plan view of a surface of the second dielectric layer 105 when viewed from the upper side, the part corresponding to each part of the concave portion 106 is denoted by a numeral with parenthesis. When the concave portions are formed in this manner, the electrical charge is more stably held. Further, the concave portions of this shape and arrangement make it possible to use the same reticle in production process employing semiconductor process even when a pattern of the electret layer 107 (the pattern of electret element in the case of forming a plurality of electret elements 100a to 100c as shown in FIG. 3) is changed.

The injection of the electrical charge to the electret layer 107 is conducted by, for example, corona discharging. The electrical charge is injected into one or both of the first dielectric layer 104 and the second dielectric layer 105 in the electret layer 107. The polarity of the injected electrical charge may be positive or negative.

In this embodiment, the electrically-conductive electrode 103 is connected to an earth potential. Alternatively, the electrically-conductive electrode 103 may be connected to a potential which is of the same polarity as that of the electrical charge held in the electret layer 107 and has an absolute value being smaller than the absolute value of a surface potential of the electret layer 107, or a potential which is of a polarity different from that of the electrical charge held in the electret layer 107. For example, when the negative electrical charge is held in the electret layer 107 and the surface potential of the electret layer 107 is -250 V, the electrically-conductive electrode 103 may be connected to a potential which is lower than the surface potential, for example, a potential of -240 V to +750 V. Alternatively, when the positive electrical charge is held in the electret layer 107 and the surface potential of the electret layer 107 is +250 V, the electrically-conductive electrode 103 may be connected to a potential of -750 V to +240 V. Further, the surface potential of the electret layer 107 and the potential of the electrically-conductive electrode 103 may be selected such that the difference between these potentials is not over a dielectric strength voltage of the electret layer. Such selection suppresses the outflow of the electrical charge due to insulation breakdown, or loss of the electret characteristics due to the formation of a leak path.

Further, a distance between two adjacent concave portions 106 (which corresponds to a length of a line connecting centers of the bottom faces 106a in FIG. 1) is preferably larger than a thickness of the first dielectric layer 104. The thickness of the first dielectric layer 104 is a thickness determined at the thinnest point (the thickness at the bottom

face). This prevents the electrical charge from flowing out due to linear movement of the electrical charge between the bottom faces **106a** because of hopping conduction or the like when the difference in potential is observed between the bottom faces **106a** of the two adjacent concave portions **106** within the amount of electrical charge which can be held in the first dielectric layer **104** (a product of a dielectric voltage (MV/cm) of the first dielectric layer **104** and the thickness of the first dielectric layer **104**).

The substrate **101** is a monocrystalline silicon substrate which is doped an impurity and is an electrically-conductive substrate having conductivity. The third dielectric layer **102** is a silicon oxide film having a thickness of 1 μm , which is formed by oxidizing the substrate **101** by a thermal oxidation method. The electrically-conductive electrode **103** is a polycrystalline silicon film having a thickness of 300 nm, which is doped with an impurity. The first dielectric layer **104** is a silicon oxide film having a thickness of 1000 nm, which is formed by a LPCVD (Low pressure chemical vapor deposition) method and the second dielectric layer **105** is a silicon nitride film having a thickness of 150 nm, which is formed by the LPCVD method. The concave portion **106** in the first dielectric layer **104** is formed by dry etching. In the concave portion **106**, a width of the bottom face **106a** is 5 μm and the width of the top face **106c** is 5 μm . The interval between adjacent concave portions **106** (a distance between centers of adjacent bottom faces **106a**, which is referred to as "pitch") is 10 μm and the depth is 350 nm. Further, the side wall **106b** is inclined in the concave portion **106**.

FIG. 3 shows a cross-sectional view of a vibration power generating device **600** provided with the electret element **100** of the present embodiment. The vibration power generating device **600** includes electret elements **100a** to **100c** (wherein the substrate **101** constituting the electret elements **100a** to **100c** is a common single substrate) which are formed by patterning the electret layer **107** and the electrically-conductive electrode **103**, a substrate **603** with collector electrodes **607** which is arranged opposed to the electret elements with a predetermined gap. Both ends of the substrate **101** are connected to fixing structures **610** via elastic structures **609**. The elastic structure **609** may be a spring or may be formed of a material which pushes back the substrate **101** due to repulsion (for example, rubber).

When vibration **608** is applied from the outside, the elastic structure **609** stretches and contracts, and thereby the substrate **101** relatively moves to the substrate **603**. At this time, the overlapped areas between the electret elements **100a** to **100c** and the collector electrodes **607a** to **607c** are changed, resulting in increase and decrease in an amount of electrical charge induced in the collector electrodes **607a** to **607c**. The power generation is conducted by taking out this change in electrical charges as electrical energy. The vibration power generating device **600** may be used in, for example, a wireless communication module which consumes small power, and other electronic devices.

The electret element **100** according to the present embodiment can give the effect of improving the electrical charge-holding stability of the electret. This effect will be described below in detail.

The electrical charge injected and held in the electret element **100** diffuses and flows out with time by electrostatic repulsion force acted on the held electrical charges, from the inside of the electret element **100** where the charge density is high to the outside of the electret element **100** where the charge density is low. At this time, the electrical charge held inside the electret element **100** flows out passing through the region where the insulation properties are low, of the inside

of the electret element **100**. The bonded interface between the first dielectric layer **104** and the second dielectric layer **105** which constitute the electret element **100**, is a bonded face of different materials of the first dielectric layer **104** and the second dielectric layer **105**. Since the bonded face is a region where more lattice defects exist, the bonded face is less insulative. Therefore, the electrical charge held inside the electret element **100** tends to move along the bonded interface between the first dielectric layer **104** and the second dielectric layer **105** and flow out.

As shown in FIG. 1, the bonded interface between the first dielectric layer **104** and the second dielectric layer **105** extends in the direction away from the electrically-conductive electrode **103** ("z" direction in FIG. 1) at the side wall **106b** of the concave portion. Therefore, when the electrical charge held inside the electret element **100** moves along the bonded interface between the first dielectric layer **104** and the second dielectric layer **105**, the electrical charge moves in the direction away from the electrically-conductive electrode **103** ("z" direction in FIG. 1). On the other hand, the electrical charge held inside the electret element **100** is drawn to the electrically-conductive electrode **103** by electrostatic force since the electrically-conductive electrode **103** is connected to an earth potential in this embodiment. Thus, even if the electrical charge tries to move in the direction away from the electrically-conductive electrode **103** ("z" direction in FIG. 1) along the bonded interface between the first dielectric **104** and the second dielectric **105**, the electrical charge cannot move from the bottom region of the concave portion **106** because the electrostatic force pulling the charge toward the electrically-conductive electrode **103** acts on the charge. This prevents the outflow of the electrical charge and the electrical charge is held stably in the bottom face **106a** of the concave portion **106**. This is applicable to the case where the electrically conductive electrode **103** is connected to: a potential which is of the same polarity as that of the electrical charge held by the electret layer **107** and has an absolute value being smaller than the absolute value of a surface potential of the electret layer **107**; or a potential which is of a polarity different from that of the electrical charge held in the electret layer **107**.

In the present embodiment, a configuration having a plurality of concave portions **106** is shown. In a first variation, a first dielectric layer **134** of one electret element **300** may have only one concave portion **136**, as shown in FIG. 4. In this case, it is easy for a second dielectric layer **135** to cover a bottom face and a side wall of the concave portion **136** since the size of the concave portion **136** can be increased.

In an electret element **310** of a second variation, a second dielectric layer **145** may be formed such that it covers only a bottom face **146a** and a side wall **146b** of a concave portion **146** in a first dielectric layer **144** as shown in FIG. 5. Alternatively, in an electret element **320** of a third variation, a second dielectric layer **155** may cover only a bottom face **156a** and a part of side wall **156b** of a concave portion **156** in a first dielectric layer **155** as shown in FIG. 6. Also in these variations, the electrical charges which move the bonded interfaces between the first dielectric layers **144** and **154** and the second dielectric layer **145** and **155** cannot flow out unless they move in the "z" direction. However, in these variations, the movement of the electrical charges in the "z" direction is suppressed by the electrostatic force, and therefore the electrical charges can be stayed within the concave portions **146** and **156** and the electrical charge-holding stability is improved.

11

In an electret element **330** of a fourth variation of the present embodiment, a thickness of a second dielectric layer **165** may be larger than a distance from a bottom face to a top face of a concave portion **166** in a first dielectric layer **164**, as shown in FIG. 7. Further, in a fifth variation (which is a variation of the fourth variation), an electret element **340** may have only one concave portion **176** as shown in FIG. 8. In these variations, the thicknesses of the second dielectric layers **165** and **175** are larger than the depths of the concave portions **166** and **167** in the first dielectric layers **164** and **174** so as to bury the concave portions **166** and **176** with the second dielectric layers **165** and **175**, whereby the second dielectric layers **165** and **175** do not discontinue, for example at the side walls of the concave portions and the bottom faces and the side walls of the concave portions are continuously and satisfactorily covered with the second dielectric layers **165** and **175**.

In an electret element **350** of a sixth variation of the present embodiment, one or more dielectric layers **187** may be formed between an electrically-conductive electrode **183** and a first dielectric layer **184** and thereby an electret layer **180** may consist of three dielectric layers **185**, **184** and **187** as shown in FIG. 9. In this case, an amount of electrical charge which is capable of being held in the electret layer **180** can be increased. For example, the dielectric breakdown occurs when electric field larger than about 5 MV/cm to about 7 MV/cm is applied in the electret of a silicon oxide film. Therefore, when the thickness of the silicon oxide film as the first dielectric layer **184** is 1 μm , the limit of surface potential is 500 V.

On the other hand, when another dielectric layer **187** is formed between the electrically-conductive electrode **183** and the first dielectric layer **184**, the limit of surface potential can be increased by a product of the dielectric voltage (MV/cm) and the thickness of the another dielectric layer **187**. As a result, the surface potential of the electret element **350** can be increased and the electrostatic induction characteristics of the electronic device using the electret element **350** can be increased. As a result, when the electret element **350** is applied to, for example, a vibration power generating device, the output power can be increased.

In an electret element **400** of a seventh variation of the present embodiment, a moisture-proof layer **208** may be formed on a surface of the second dielectric layer **105** as shown in FIG. 10. The moisture proof layer **208** prevents the electrical charge in the electret layer **107** from being deprived by the moisture in the air, and thereby the electrical charge-holding stability can be further improved. The moisture-proof layer may be HMDS (hexa methyl disilane) wherein a hydrophobic group prevents water adsorption, BCB (benzocyclobutene) or a high gas-barrier inorganic material (for example, a silicon oxide film, a silicon nitride film or an aluminum oxide film). The moisture-proof layer is formed such that, when a portion of surface of the first dielectric layers **144** and **154** is not covered with the second dielectric layer (**145** and **155**) and is exposed as in the electret elements **310** and **320** as shown in FIGS. 5 and 6, the exposed region is also covered with the moisture-proof layer.

In an electret element **410** of an eighth variation of the present embodiment, an electrically-conductive substrate **211** may be used instead of the electrically-conductive electrode and a substrate and the substrate **211** may be connected to an earth potential as shown in FIG. 11. In the case of using the electrically-conductive substrate, the electrical charge-holding stability can be improved. The electrically-conductive substrate **211** may be connected to a poten-

12

tial which is of the same polarity as that of the electrical charge held in the electret layer **107** and has an absolute value being smaller than the absolute value of a surface potential of the electret layer **107**, or a potential which is of a polarity different from that of the electrical charge held in the electret layer **107**. Since this construction does not require the third dielectric layer and the electrically-conductive electrode, the construction of electret element is simplified and has advantage in costs.

In the present embodiment, an example wherein the concave portions **106** (more strictly, the bottom faces **106a** and the top faces **106c** of the concave portions) have a rectangular shape and are disposed parallel to each other as shown in FIG. 2 is illustrated. In a ninth variation, a plurality of concave portions **306** may be formed in a first dielectric layer **506** such that a plurality of bottom faces **306** and a plurality of top faces **306c** are concentric in one single electret element **500** as shown in FIG. 12. In this case, the outflow of electrical charge can be prevented in all the direction in the "x-y" plane. FIG. 12 and FIGS. 13 to 15 which will be described below are plan views of the element from which the second dielectric layer is removed, that is, plan views of the first dielectric layer. In these variations, the side wall of the concave portion is not inclined, but the side wall may be inclined or may be curved. Further, in FIG. 12 and FIGS. 13 to 15, the portions correspond to the bottom faces **306a**, **316a**, **326a** and **336a** are hatched for easy seeing.

Alternatively, as shown in FIG. 13, a plurality of concave portions **316** which are of frame-like shape and similar figures may be formed in a first dielectric layer **316** in one single electret element **510** (a tenth variation) such that the bottom faces **316a** and the top faces **316c** are concentric. Such concave portions **316** can be formed by a semiconductor process using lithography more easily compared to the concave portions of concentric circles.

Alternatively, as shown in FIG. 14, concave portions **326** may be formed in a first electret layer **326** in one single electret element **520** (an eleventh variation) such that the bottom faces **326a** form dot pattern. In this configuration, the top face **326c** is a plane connecting the dots **326a**. When this configuration is formed by the semiconductor process using lithography, the same reticle can be used irrespective of the shapes of the first dielectric layer and the second dielectric layer. Therefore, if the pattern shapes of the first dielectric layer and the second dielectric layer are changed, there is no need to remake the reticle.

Alternatively, as shown in FIG. 15, concave portions **336** may be formed in the first dielectric layer **336** in one single electret element **530** (an twelfth variation) such that square bottom faces **336a** are formed regularly and the top face **336b** is formed into lattice shape. Such concave portion **336** can be formed by the semiconductor process using the lithography more easily compared to the concave portion of the concentric circular.

In the present embodiment, the substrate **101** is a silicon substrate. The substrate **101** may be a sapphire substrate or a glass substrate, or a substrate of another material. When an insulative substrate (the glass substrate or the sapphire substrate) is used as the substrate **101**, an electret element **650** (a thirteenth variation) does not need to have a third dielectric layer and the electrically-conductive electrode **103** may be formed on a substrate **651** as shown in FIG. 16.

In the present embodiment, the first dielectric layer **104** is a silicon oxide film and the second dielectric layer **105** is a silicon nitride film. In the case where negative electrical charge is charged in the electret layer of laminate structure

13

wherein the first dielectric layer is disposed closer to the substrate and the second dielectric layer is disposed farther from the substrate, the second dielectric layer is not limited particularly as long as a bottom Ec of conductive band of the second dielectric layer is lower than that of the first dielectric layer. In the case where positive electrical charge is charged in the electret layer of the same structure, the second dielectric layer is not limited particularly as long as a top Ev of valence band of the second dielectric layer is higher than that of the first dielectric layer. When these two dielectric layers have energy levels satisfying these relationships, the first dielectric layer becomes a potential barrier against the electrical charge charged in the electret layer.

For example, the second dielectric layer **105** may be an aluminum oxide film, a hafnium oxide film, or a titanium oxide film. These films are dielectric films against which the silicon oxide film is capable of being the potential barrier, and therefore the combination of any one of these films and the silicon oxide film can effectively improve the thermal resistance of the electret layer.

The electrically-conductive electrode **103** may be formed from a material other than polysilicon, for example, a metal material (for example, aluminum or copper). When the metal material is used, a resistivity of the electrode can be lowered. Therefore, if the electret element **100** wherein the electrically-conductive electrode is formed from the metal material is used in the vibration power generating device, the power loss due to heat generation at resistor can be reduced. As a result, the electrical charge induced by electrostatic induction can be output effectively.

Examples

Specific examples of the above-mentioned embodiment will be described as examples. It should be noted that the present invention is not restricted to the following examples.

An electret element **700** as shown in FIG. **17** was manufactured and the electrical charge-holding stability was evaluated. A silicon oxide film **704** having a thickness of 1 μm was formed on a silicon substrate **701** (thickness 675 μm) by thermal oxidation method. Further, a plurality of concave portions **706** of rectangular shape were formed in a surface of the silicon oxide film **704** which surface is on the side of the principal surface of the silicon substrate **701** by dry etching. The concave portion **706** has a bottom face **706** having a width of 5 μm , and the depth of the concave portion **706** was 350 nm, and the pitch of the bottom face **706a** was 10 μm . The concave portions **706** were formed parallel to each other. A silicon nitride film **705** (having a thickness of 150 nm) was formed on the silicon oxide film **704** with concave portions **706** by the LPCVD method. Finally, HMDS was vapor-deposited as a moisture-proof layer **708** and positive electrical charge was injected in the electret layer **707** by corona discharging.

[Evaluation of Electrical Charge-Holding Stability]

The electret element **700** manufactured by the above-mentioned method was stored in environment of high-humidity (30° C. and 85% RH) which accelerates the outflow of the electrical charge and the electrical charge-holding stability was evaluated. The surface potential was determined using a surface potential meter (manufactured by TREK Inc., model 347). The evaluation results are shown in FIG. **18**. Comparison of the degradation rate of the surface potential after a lapse of 200 hours in the environment of high humidity relative to an initial potential was made for the electret element according to an embodiment of the present invention and the conventional electret element. The

14

conventional electret element (having the same configuration as that of the electret element shown in FIG. **17** except that the concave portion was not formed in the first dielectric layer) showed about 35% decrease in surface potential, while the electret element of the present embodiment showed about 1% decrease in surface potential. From these results, it can be said that the electret element of the present embodiment presents higher electrical charge-holding stability compared to the conventional electret which is of the same film structure and same film thickness, but does not have the concave structure.

The embodiments illustrated in the drawings are mere examples of the embodiments. The number, shape, size and depth of the concave portions, the thickness of the dielectric layer, the amount of electrical charge held in the dielectric layer, and the shape and the number of the electrically-conductive electrodes are not limited particularly. The effect of the present embodiment can be obtained by arbitrarily selecting these factors.

Further, the above-mentioned embodiment merely exemplifies the present invention, and various modification, replacement, addition and omission may be made within the attached claims and equivalent thereof.

The electret element of the present invention has improved electrical charge-holding stability and is useful as the electret electrode for a vibration power generating device.

What is claimed is:

1. An electret element comprising a substrate, an electrically-conductive electrode, and an electret layer comprising a first dielectric layer and a second dielectric layer, wherein: the electret layer is capable of holding electrical charge; the electrically-conductive electrode is on a surface of the substrate; the first dielectric layer is on a surface of the electrically-conductive electrode and has, in a surface opposite to an electrically-conductive electrode-side surface, at least one concave portion having a bottom face, a side wall and a top face; the second dielectric layer covers the entirety of the bottom face and at least a part of the side wall; and a bottom Ec of a conductive band of the second dielectric layer is lower than a bottom Ec of a conductive band of the first dielectric layer, or a top Ev of a valence band of the second dielectric layer is higher than a top Ev of a valence band of the first dielectric layer, wherein a thickness of the first dielectric layer between the bottom face and the surface of the electrically-conductive electrode is thinner than a thickness of the first dielectric layer between the top face and the surface of the electrically-conductive electrode.
2. The electret element according to claim 1, wherein the electret layer further comprises at least one dielectric layer and the at least one dielectric layer is between the electrically-conductive electrode and the first dielectric layer.
3. The electret element according to claim 1, wherein the electrical charge is held in the electret layer and the electrically-conductive electrode is connected to:
 - a potential which is of a same polarity as that of the electrical charge and has an absolute value being smaller than the absolute value of a surface potential of the electret layer; or
 - a potential which is of a polarity different from that of the electrical charge.
4. The electret element according to claim 1, wherein the electrically-conductive electrode is connected to an earth potential.

15

5. The electret element according to claim 1, wherein the first dielectric layer is a silicon oxide film and the second dielectric layer is a film selected from the group consisting of a silicon nitride film, an aluminum oxide film, a hafnium oxide film and a titanium oxide film.

6. The electret element according to claim 1, further comprising a third dielectric layer, wherein the substrate is an electrically-conductive substrate and the third dielectric layer is between the electrically-conductive substrate and the electrically-conductive electrode.

7. The electret element according to claim 6, wherein the electrically-conductive substrate is a silicon substrate, the third dielectric layer is a silicon oxide film and the electrically-conductive electrode consists of polycrystalline silicon.

8. The electret element according to claim 1, wherein the substrate is an insulative substrate.

9. The electret element according claim 8, wherein the insulative substrate is a glass substrate or a sapphire substrate, and the electrically-conductive electrode consists of a material selected from the group consisting of polycrystalline silicon, aluminum and copper.

10. The electret element according to claim 1 wherein an electrically-conductive substrate is substituted for the substrate and the electrically-conductive electrode, and the first dielectric layer is on a surface of the electrically-conductive substrate.

11. The electret element according to claim 10, wherein the electrical charge is held in the electret layer and the electrically-conductive substrate is connected to:

- a potential which is of a same polarity as that of the electrical charge and has an absolute value being smaller than the absolute value of a surface potential of the electret layer; or
- a potential which is of a polarity different from that of the electrical charge.

12. The electret element according to claim 10, wherein the electrically-conductive substrate is connected to an earth potential.

16

13. The electret element according to claim 1, wherein a depth from the top face to the bottom face of the at least one concave portion is larger than a thickness of the second dielectric layer.

14. The electret element according to claim 1, wherein the at least one concave portion includes a plurality of the concave portions, and an interval between two adjacent concave portions of the plurality of concave portions is larger than a thickness of the first dielectric layer.

15. The electret element according to claim 1, further comprising a moisture-proof layer, wherein the moisture-proof layer covers:

- a surface of the second dielectric layer; or
- the surface of the second dielectric layer and a region of the surface of the first dielectric layer, which region is not covered with the second dielectric layer.

16. A vibration power generating device which is provided with the electret element according to claim 1.

17. The electret element according to claim 1, wherein the side wall is inclined or curved.

18. The electret element according to claim 1, further comprising an interface between the first dielectric layer and the second dielectric layer, wherein the interface extends in a direction away from the electrically-conductive electrode at the side wall of the at least one concave portion, such that in operation, when the electrical charge tries to move along the interface between the first dielectric layer and the second dielectric layer in the direction away from the electrically-conductive electrode, the electrical charge is drawn to the electrically-conductive electrode by electrostatic force.

19. The electret element according to claim 1, further comprising an interface between the first dielectric layer and the second dielectric layer, wherein, in operation, electrostatic force attracts the electrical charge to the bottom region of the at least one concave portion.

20. The electret element according to claim 1, wherein a top region of the at least one concave portion is wider than a bottom region of the at least one concave portion.

21. The electret element according to claim 1, wherein an interface between the electrically-conductive electrode and the first dielectric layer is flat.

* * * * *